PRINCIPLES OF PHYSICAL GEOLOGY

PLATE I

[*Hillers, U.S. Geol. Survey*

Grand Canyon of the Colorado River, Arizona

PRINCIPLES OF PHYSICAL GEOLOGY

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95 Plates and 262 Text Illustrations

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PREFACE

LIKE many other teachers of geology and geography in this country, I have long felt the need for a thoroughly up-to-date book on Physical Geology. I therefore readily responded when the publishers invited me to write the sort of book that seemed to be required. The method of treatment adopted is one that twenty years' experience has shown to be successful in training students and in holding and developing their interest, even when, as has often been the case, some of them have come to the subject without any preliminary acquaintance with scientific principles and methods. For this reason it is hoped that the book will appeal not only to students and teachers and to the senior classes in schools, but also to the general reader who wishes to see something of the " wild miracle " of the world we live in through the eyes of those who have tried to resolve its ancient mysteries.

The earth's activities may be compared to an intricate interplay of combined operations, and the results, whether they be landscapes, natural catastrophes, or materials such as building stones and fuels, are correspondingly varied. It is inherent in the character of the subject that the full significance of any one aspect can be properly appreciated only in relation to the whole. A broad preliminary survey has therefore been presented in Part I, to serve as an introduction to the more detailed treatment that follows. Part II deals with the outer earth and only turns aside from tracks already familiar to take in the more interesting results achieved by recent progress. Part III is mainly concerned with the activities of the inner earth and their surface expressions. Thanks to the variety of detective methods that have been developed during the present century, the depths are less inscrutable than formerly and the time is ripe for the incorporation into an elementary book of the many spectacular discoveries that have already been made. But even so, the frontiers of established knowledge are soon reached, and what we think we see by peering beyond is merely

interpretation, and must on no account be confused with the solid facts of observation. While I have not hesitated to introduce current views, since these reveal the active growth of the subject, it should be clearly realized that topics such as the cause of mountain building, the source of volcanic activity and the possibility of continental drift remain controversial just because the guiding facts are still too few to provide a foundation for more than tentative hypotheses. It is my hope that recognition of some of the outstanding problems may stimulate at least a few of my readers to co-operate in the attempt to solve them.

Professor Alfred Brammall, Dr. Leonard Hawkes and my wife (Dr. Doris L. Reynolds) have given generous assistance by reading the first draft of the book, and I gratefully acknowledge that the subsequent revision owes much to their constructive criticism and helpful suggestions. For any defects that still remain—whether of fact, treatment, judgment or style—I am, of course, entirely responsible.

As befits the subject, special care has been taken to illustrate the book as fully and effectively as possible. Of the 262 text-figures over two hundred have been specially drawn. Some of the figures are original, others are based on diagrams already published, and a few have been directly reproduced with due acknowledgment. In addition to the photographs procured from professional photographers and press agencies, many more have been contributed by various friends and official organizations. It is a pleasure to record my cordial thanks to the following :

The Director of H.M. Geological Survey, for fifty subjects selected from the Survey's unrivalled collection of British geological photographs. Copyright of these is reserved by the Crown, and this has been specifically stated beneath eleven of the reproductions, to indicate that they are included by permission of the Controller of H.M. Stationery Office.

The Director of the United States Geological Survey, and also the National Park Service and the Department of the Interior of the United States, for providing batches of photographs from which many striking and instructive subjects have been selected.

The Director-General of the South African Air Force, for supplying the originals of Figs. 69 and 81 and Plate 87A, which are " air photographs published under the Union of South Africa Government Printer's Copyright Authority No. 489 of 12.11.42," and of Plates 30, 45A and 88, which were taken by the Aircraft Operating Company of South Africa Limited.

The Curator of the Belfast Municipal Museum and Art Gallery for permission to use three photographs (Plates 8A, 17A, and 35B) from the well-known series taken by the late Mr. R. Welch.

The Geological Photographs Committee of the British Association (Fig. 18 and Plate 74B) ; the Egyptian Government (Plate 62A and B) ; the Burma Forest Service (Plate 75B) ; and the Burmah Oil Company Limited (Plate 77B).

A word of personal appreciation is due to Mr. F. N. Ashcroft for the privilege of using ten of his superb geological photographs. Other friends and correspondents to whom I am indebted for illustrative material are Capt. J. Brown, Mr. F. A. Bannister, Dr. H. S. Bell, Dr. A. J. Bull, Dr. A. M. Cockburn, Dr. R. M. Craig, Mr. A. D. Combe, Prof. R. A. Daly, Dr. D. Griggs, Dr. L. Hawkes, Prof. H. G. A. Hickling, Dr. W. F. Hume, Prof. A. Lacroix, Dr. C. E. Marshall, Mr. G. O'Neill, Prof. S. H. Reynolds, the late Dr. R. W. Sayles, Mr. G. S. Sweeting, Dr. C. T. Trechmann, Dr. G. W. Tyrrell, Prof. W. W. Watts, Mr. E. J. Wayland and Dr. C. E. Wegmann.

It will be noticed that the illustrations are not listed in the preliminary pages. When such lists become unduly long, as would here have been the case, they tend to defeat their purpose. As an alternative which it is hoped will facilitate easy reference, the plates and text-figures are included in the index.

ARTHUR HOLMES

DURHAM
July 1942

EDINBURGH
May 1944

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PART I A PRELIMINARY SURVEY

CHAPTER I

INTRODUCTION

INTERPRETATIONS OF NATURE: ANCIENT AND MODERN

THE world we live in presents an endless variety of fascinating problems which excite our wonder and curiosity. The scientific worker, like a detective, attempts to formulate these problems in accurate terms and, so far as is humanly possible, to solve them in the light of all the relevant facts that can be collected by observation and experiment. Such questions as What? How? Where? and When? challenge him to find the clues that may suggest possible replies. Confronted by the many problems presented by, let us say, an active volcano (Plate 2), we may ask: What are the lavas made of? How does the volcano work and how is the heat generated? Where do the lavas and gases come from? When did the volcano first begin to erupt and when is it likely to erupt again?

Here and in all such queries the question What? refers to the stuff things are made of, and an answer can be given in terms of chemical compounds and elements. Not the elements of ancient philosophers, who considered the ultimate ingredients of things to be earth, air, fire, and water, but chemical elements such as oxygen, silicon, iron, and aluminium.

The question How? refers to processes—the way things are made or happen or change. The ancients regarded natural processes as manifestations of power by capricious and irresponsible gods. In the Mediterranean region, for example, Poseidon was regarded as the ruler of the seas and underground waters. As the waters confined below the surface struggled to escape,

Poseidon assisted them by shaking the earth and fissuring the ground. He thus became the god of earthquakes. Typhon, the source of destructive winds, was a " many-headed monster of malignant ferocity " imprisoned in the earth. From him the dreaded typhoon takes its name. Pluto was the deity presiding over the fiery regions of the underworld. The eruptions of lavas and volcanic bombs from Stromboli and Vesuvius were expressions of his wrath. In Ireland, on the other hand, legendary giants made things happen. They were stone throwers and builders. One of them flung the Isle of Man into the Irish Sea and Lough Neagh represents the place it was taken from. The Giant's Causeway (Plate 3B), which is a terrace carved by the weather and the sea from an ancient lava flow of columnar basalt, was " explained " as the work of the giant Fionn MacComhal.

To-day we think of natural processes as manifestations of energy acting on or through matter. We no longer blindly accept events as results of the unpredictable whims of mythological beings. Typhoons and hurricanes are no longer interpreted as the destructive breath of a wind god : they arise from the heating of the air over sun-scorched lands. The source of the energy is heat from the sun. Volcanic eruptions and earthquakes no longer reflect the erratic behaviour of the gods of the underworld : they arise from the action of the earth's internal heat on and through the surrounding crust. The source of the energy lies in the material of the inner earth. In many directions, of course, and particularly where great catastrophes are concerned, our knowledge is still woefully incomplete. Only the first of the questions we have asked about volcanoes can as yet be satisfactorily answered. The point is not that we now pretend to understand everything—if we did, the task of science would be over—but that we have faith in the orderliness of natural processes. As a result of two or three centuries of scientific investigation we have come to believe that Nature is understandable in the sense that if we ask her questions by way of appropriate observation and experiment, she will answer truly and reward us with discoveries that endure.

[G. Sommer

Paroxysmal eruption of Vesuvius, 26th April 1872

PLATE 3

[E.N.A.

(A) Fingal's Cave, Island of Staffa, west of Mull, Argyllshire

[E.N.A.

(B) The Giant's Causeway, Co. Antrim

COLUMNAR BASALTS

The Major Fields of Scientific Study

The questions we ask when faced with a volcano in eruption are typical of the kinds suggested by all natural phenomena. They indicate that—in general terms—scientific investigation is concerned with the manifestations and transformations of matter and energy in space and time.

Of all the sciences *Physics* is the most fundamental, for it deals with all the manifestations of energy and with the nature and properties of matter in their most general aspects. It overlaps to some extent with *Chemistry*, which is particularly concerned with the composition and interactions of substances of every kind in terms of atoms and molecules, elements and compounds. *Biology* is the science of living matter. The nature of life still remains an elusive mystery, completely inexplicable in terms of matter and energy alone, but living organisms and their evolution can nevertheless be investigated scientifically. All other sciences are restricted to more or less specific fields of interest. *Astronomy* claims the unfathomed universe of stars and nebulæ as its field of study. It is concerned with the distribution and movements of matter in space on a celestial scale. Its interest in the earth is limited to the purely planetary aspects of our globe. Regarded as a daughter of the sun, the earth may be only an insignificant speck in the immensity of space. But the earth is also the mother of life and the home of mankind, and as such we naturally regard her as the most important of all the celestial bodies. Thus the earth remains as a special field for investigation, and to this is devoted the science appropriately known as *Geology* (from the Greek *Ge*, the earth ; *logos*, logical speech or " science ").

From the earliest days of exploration *Geography* has been recognized as the study of the " home of mankind." Modern geography focuses attention on man's physical, biological, and cultural environment and on the relationships between man and his environment. The study of the physical environment by itself is Physical Geography, which includes consideration
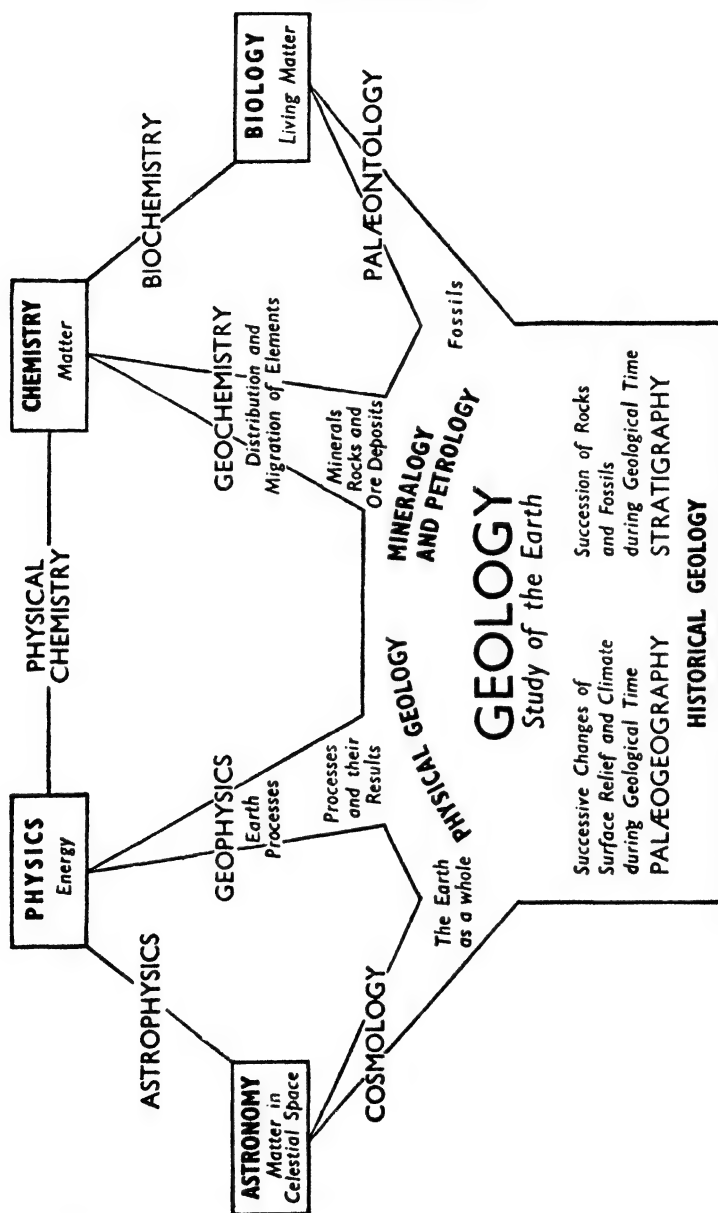
Fig. 1

Subdivisions of the science of geology and their relations to other sciences

of the surface relief of the globe (Geomorphology), of the seas and oceans (Oceanography), and of the air (Meteorology and Climatology). Partly as an offshoot from early geography and partly from the observations of miners, but mainly from the work of amateur collectors of minerals, rocks, and fossils, there developed the more general science of the earth which is distinguished as *Geology*.

The Scope and Subdivisions of Geology

Modern geology has for its aim the deciphering of the whole evolution of the earth and its inhabitants from the time of the earliest records that can be recognized in the rocks right down to the present day. So ambitious a programme requires much subdivision of effort, and in practice it is convenient to divide the subject into a number of branches, as shown in Fig. 1, which also indicates the chief relationships between geology and the other major sciences. The key words of the three main branches are the *materials* of the earth's rocky framework (Mineralogy and Petrology) ; the geological processes or *machinery* of the earth, by means of which changes of all kinds are brought about (Physical Geology) ; and finally the succession of these changes, or the *history* of the earth (Historical Geology).

The earth is made up of a great variety of materials, such as air, water, ice, and living organisms, as well as minerals and rocks and the useful deposits of metallic ores and fuels which are associated with them. The relative movements of these materials (wind, rain, rivers, waves, currents, and glaciers ; the growth and movements of plants and animals ; and the movements of hot materials inside the earth, as witnessed by volcanic activity) all bring about changes in the earth's crust and on its surface. The changes involve the development of new rocks from old ; new structures in the crust ; and new distributions of land and sea, mountains and plain, and even of climate and weather. The scenery of to-day is only the latest stage of an ever-changing kaleidoscopic series of widely

varied landscapes—and seascapes. *Physical Geology* is concerned with all the terrestrial agents and processes of change and with the effects brought about by them. This branch of geology is by no means restricted to geomorphology, the study of the surface relief of the present day, which it shares with physical geography. Its main interest, as we have seen, is in the machinery of the earth, past and present, and in the various by-products, of which the existing surface relief and the rocks now in process of formation are important examples.

Changes of all kinds have been going on continuously for something like 2,000 million years. To a geologist a rock is more than an aggregate of minerals ; it is a page of the earth's autobiography with a story to unfold, if only he can read the language in which the record is written. Placed in their proper order from first to last (*Stratigraphy*), these pages embody the history of the earth. Moreover, it is familiar knowledge that many beds of rock contain the remains or impressions of shells or bones or leaves. These objects, called fossils, are the relics of animals or plants that inhabited the earth in ancient times. *Palæontology* is the study of the remains of these ancestral forms of life. Thus we see that *Historical Geology* deals not only with the sequence of events brought about by the operation of the physical processes, but also with the history of the long procession of life through the ages.

Geology is by no means without practical importance in relation to the needs and industries of mankind. Thousands of geologists are actively engaged in locating and exploring the mineral resources of the earth. The whole world is being searched for coal and oil, and for the ores of the useful metals. Geologists are also directly concerned with the vital subject of water supply. Many engineering projects, such as tunnels, canals, docks, and reservoirs, call for geological advice in the selection of sites and materials. In these and many other ways, geology is applied to the service of mankind.

Although geology has its own laboratory methods for studying minerals, rocks, and fossils, it is essentially an open-air science. It attracts its followers to crags and waterfalls, glaciers and volcanoes, beaches and coral reefs, ever farther

and farther afield in the search for information about the earth and her often puzzling behaviour. Wherever rocks are to be seen in cliffs and quarries, their arrangement and sequence can be observed and their story deciphered. With his hammer and maps the geologist in the field leads a healthy and exhilarating life. His powers of observation become quickened, his love of Nature in all her moods is deepened, and the thrill of discovery is ever at hand.

SUGGESTIONS FOR FURTHER READING

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The Scientist in Action. Williams and Norgate, London, 1936.

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Chapter II

THE SHAPE AND SURFACE RELIEF OF THE EARTH

The Outer Zones of the Earth

As it presents itself to direct experience, the earth can be physically described as a ball of rock (the lithosphere), partly covered by water (the hydrosphere) and wrapped in an envelope of air (the atmosphere). To these three physical zones it is convenient to add a biological zone (the biosphere).

The *Atmosphere* is the layer of gases and vapour which envelopes the earth. It is essentially a mixture of nitrogen and oxygen with smaller quantities of water vapour, carbon dioxide, and inert gases such as argon. Geologically it is important as the medium of climate and weather, of wind, cloud, rain, and snow.

The *Hydrosphere* includes all the natural waters of the outer earth. Oceans, seas, lakes, and rivers cover about three-quarters of the surface. But this is not all. Underground, for hundreds and even thousands of feet in some places, the pore spaces and fissures of the rocks are also filled with water. This ground-water, as it is called, is tapped in springs and wells, and is sometimes encountered in disastrous quantities in mines. Thus there is a somewhat irregular but nearly continuous mantle of water around the earth, saturating the rocks, and over the enormous depressions of the ocean floors completely submerging them. If it were uniformly distributed over the earth's surface it would form an ocean about 9,000 feet in depth.

The *Biosphere*, the sphere of life, is probably a less familiar conception. But think of the great forests and prairies with their countless swarms of animals and insects. Think of the tangles of seaweed, of the widespread banks of molluscs, of reefs of coral and shoals of fishes. Add to these the inconceivable numbers of bacteria and other microscopic plants and

animals. Myriads of these minute organisms are present in every cubic inch of air and water and soil. Taken altogether, the diverse forms of life constitute an intricate and ever-changing network, clothing the surface with a tapestry that is nearly continuous. Even high snows and desert sands fail to interrupt it completely, and lava fields fresh from the craters of volcanoes are quickly invaded by the pressure of life outside. Such is the sphere of life, and both geologically and geographically it is of no less importance than the physical zones.

The *Lithosphere* is the outer solid shell or crust of the earth. It is made of rocks in great variety, and on the lands it is commonly covered by a blanket of soil or other loose deposits, such as desert sands. The depth to which the lithosphere extends downwards is a matter of definition : it depends on our conception of the crust and of what lies beneath. It is usual to regard the crust as a heterogeneous shell, possibly about 30 miles thick, in which the rocks at any given level are not everywhere the same. Beneath the crust, in what may be called the *substratum*, the material at any given level appears to be practically uniform, at least in those physical properties that can be tested. Some authors use the term " lithosphere " to include both crust and substratum.

The dominant rocks occurring in the crust fall into two contrasted groups :

(*a*) Light rocks, including granite and related types, having an average specific gravity or density * of about 2·7. Chemically these rocks are very rich in *si*lica, while *al*umina is the most abundant of the remaining constituents. Since it is often desirable to refer to them as a whole, such rocks are collectively known by the mnemonic term *sial*.

(*b*) Dark and heavy rocks, including basalt and related types (density about 2·9–3·0) and still heavier rocks (ranging in density up to about 3·4). In these *si*lica (40–50 per cent.)

* The *specific gravity* of a substance $= \frac{\text{the mass of any volume of the substance}}{\text{the mass of an equal volume of water}}$.
The *density* of a substance is the mass of unit volume of the substance, generally expressed as the mass in grams of one cubic centimetre. Since 1 c.c. of water has a mass of 1 gm., the density of water is 1. In c.g.s. units specific gravity and density are numerically the same.

is still the leading constituent, though it is much less abundant than in granite (70 per cent.). In the heavier rocks of this group *ma*gnesia takes second place, and the whole group is conveniently known as *sima*. When it is necessary to make the distinction, the basaltic rocks are sometimes referred to as *salsima*. The sial is the dominant material of the continental crust down to a depth of several miles, while the sima forms the foundations of the ocean floor and extends beneath the continents. Samples of the sima, represented by basaltic lavas, are brought to the surface by many continental and oceanic volcanoes.

Continents and Ocean Floors

The surface of the crust reaches very different levels in different places. The areas of land and sea floor between successive levels have been estimated, and the results can be
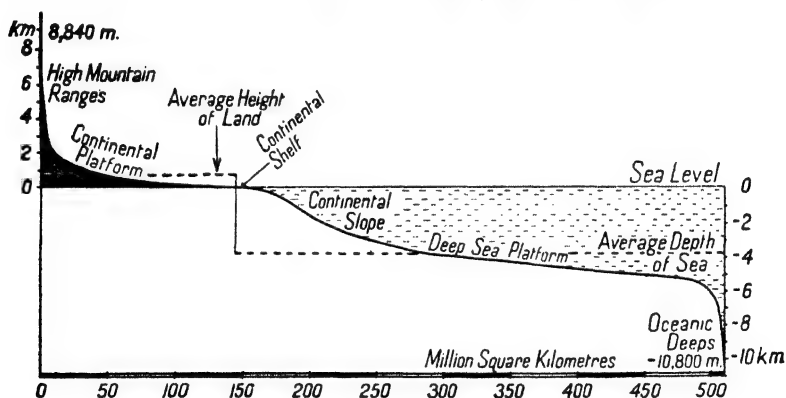
Fig. 2

Hypsographic curve, showing the areas of the earth's solid surface between successive levels from the highest mountain peaks to the deepest oceanic deeps

graphically represented as shown in Fig. 2. From this diagram it is clear that there are two dominant levels : the continental platform and the oceanic or deep-sea platform. The slope connecting them, which is actually quite gentle, is called the continental slope.

The continental platform includes a submerged outer border, known as the *continental shelf*, which extends beyond the shore zone to an average depth of about 100 fathoms or 200 metres. Structurally, the real ocean basins must be

SOME NUMERICAL FACTS ABOUT THE EARTH

Size

	Km.	*Miles*
Equatorial diameter of the earth	12,757	7,926·7
Polar diameter of the earth	12,714	7,900·0
Equatorial circumference	40,077	24,902
Polar circumference	40,000	24,860

Area

	Millions of *Sq. km.*	*Millions of* *Sq. miles*
Area of the sea floor (70·78 per cent.)	361	139·4
Area of the lands (29·22 per cent.)	149	57·5
Total area of the earth	510	196·9

Volume, Density, and Mass

	Millions of *Cu. km.*	*Millions of* *Cu. miles*
Volume of the earth	1,082,000	259,600

Density of the earth . 5·527
Mass of the earth . 5,876 million million million tons

Relief

	Metres	*Feet*	
Greatest known height: Mt. Everest	8,840	29,140	above sea level
Average height of the land	825	2,707	,, ,,
Mean level of the surface (land and sea)	250	820	,, ,,
Mean level of the lithosphere	2,450	7,040	below sea level
Average depth of the sea	3,800	12,460	,, ,,
Greatest known depth: Swire Deep	10,800	34,430	,, ,,

regarded as commencing, not at the visible shoreline, but at the edge of the shelf. The basins, however, are more than full, and the overflow of sea water inundates about 11 million square miles of the continental platform. The North Sea, the Baltic, and Hudson Bay are examples of shallow seas (epicontinental or shelf seas) which lie on the continental shelf. It is of interest to notice that during the Ice Age, when enormous quantities of water were abstracted from the oceans to form the great ice sheets that then lay over Europe and North America, much of the continental shelf must have been land. Conversely, if the ice now covering Antarctica and Greenland were to melt away, the sea level would rise and the continents would be still further submerged.

The continents themselves have a varied relief of plains, plateaus, and mountain ranges, the last rising to a maximum height of 29,140 feet (Mt. Everest). The ocean floors, except locally, are less vigorously diversified than the continents, but islands and submarine ridges and plateaus rise from their normally monotonous surfaces, and basins and deeps sink to more than average depths. The deepest sounding so far made is 34,430 feet (Swire Deep, off the Philippines). Fig. 2 might suggest that the greatest deeps are farthest away from the lands, but such is not the case. The deeps lie close in to the continental edge, and along the Asiatic side of the Pacific they are particularly strongly developed.

From the figures given above it is clear that the total vertical range of the surface of the lithosphere is just over 12 miles. To grasp the true relation between the surface relief and the earth itself, draw a circle with a radius of 2 inches. A moderately thin pencil line has a thickness of about 1/100 inch. If 2 inches represents 4,000 miles, then the thickness of the outline of the circle represents 20 miles. On this scale the relief is all contained well within the thickness of a pencil line.

Nevertheless, the relief is very great by human standards, and the question arises how it is that there are such differences of level. The earth might very well have been a smooth globe with a uniform oceanic cover. Just how it comes about that

continental land areas exist at all is still an unsolved problem. But there is no mystery in the fact that the continents stand up like platforms above the ocean floor. Like ships riding light, the continents protrude just because their rocks (sial) are light compared with the heavier rocks (sima) which underlie the ocean floor. In the same way, mountain ranges stand high above the continental platforms because the sialic rocks beneath them go down to correspondingly greater depths. High mountains have deep " roots " (see Fig. 4). To understand how these curious facts came to be ascertained, it is convenient to begin by considering the effects of gravitation and rotation on the shape of the earth.

The Shape of the Earth

The first voyage around the world, begun at Seville by Magellan in 1519 and completed at Seville by del Cano in 1522, established beyond dispute that the earth is a globe. To-day, aviators could fly round the earth in any direction in a few days. But long ago the nearly spherical form of the earth had been inferred from a variety of observations, *e.g.* the circular boundary of the earth's shadow on the moon during an eclipse, and the circularity of the horizon, wherever observed, combined with the fact that its distance * increases with the altitude of the observer.

The reason for the spherical shape of the earth became clear when Newton discovered the law of gravitation. All the particles of the earth are pulled towards the centre of gravity and the spherical shape is the natural response to the maximum possible concentration. Even if a body the size of the earth were stronger than steel, it could not maintain a shape such as, let us say, that of a cube. The pressure exerted by the weight of the edges and corners would squeeze out material in depth. Equilibrium would be reached only when

* The distance of the horizon in miles is given very closely by the simple expression $\sqrt{3h/2}$, where h is the altitude of the eye in feet. From an aeroplane at a height of 20,000 feet, for example, the aviator can see places 174 miles away.

the faces had bulged out, and the edges and corners had sunk in, until every part of the surface was equidistant from the centre.

The earth is not exactly spherical, however. Again it was Newton who first showed that, because of the earth's daily rotation, its matter is affected not only by inward gravitation, but also by an outward centrifugal force, which reaches its maximum at the equator. He deduced that there should be an equatorial bulge, where the apparent value of gravity was reduced, and a complementary polar flattening, where the centrifugal force becomes vanishingly small. Clearly, if this were so, the length of a degree of latitude across the equator would be shorter than in the far north. Expeditions were despatched to Peru in 1735 and to Lapland in 1736 to test this idea, and Newton's deduction was confirmed. If the surface of the earth were everywhere at sea level its shape would closely approximate to that of an ellipsoid of rotation (or spheroid) with a polar diameter of 7,900 miles, nearly 27 miles shorter than the equatorial diameter.

How is it, then, that the earth is not exactly a spheroid? The reason is that the crustal rocks are not everywhere of the same density. Since the equatorial bulge is a consequence of the relatively low value of gravity around the equatorial zone, it follows that there should be bulges in other places where gravity is relatively low; that is to say, wherever the outer part of the crust is composed of light sialic rocks. Such places are the continents. On the other hand, wherever the outer part of the crust is composed of heavy rocks (sima) the surface should be correspondingly depressed. Such regions are the ocean basins.

The earth is in gravitational equilibrium. If there were no rotation and no lateral differences in the density of the rocks, the earth would be a sphere. As a result of rotation it becomes a spheroid. As a further result of density differences in the crustal rocks, continents, mountain ranges, and oceanic basins occur as irregularities superimposed upon the surface of the spheroid.

Isostasy

For the ideal condition of gravitational equilibrium that controls the heights of continents and ocean floors, in accordance with the densities of their underlying rocks, the term *isostasy* (Gr. *isostasios*, "in equipoise") was proposed by Dutton, an American geologist, in 1889. The idea may be grasped by thinking of a series of wooden blocks of different heights floating in water (Fig. 3). The blocks emerge by amounts which are proportional to their respective heights ;
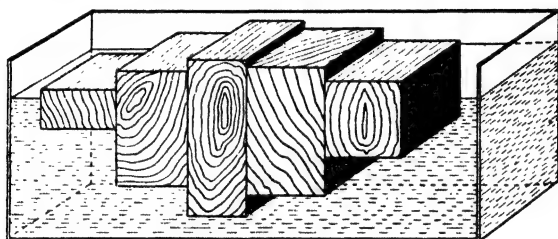
Fig. 3
Wooden blocks of different heights floating in water (shown in front as a section through the tank), to illustrate the conception of isostatic balance between adjacent columns of the earth's crust

they are said to be in a state of hydrostatic balance. Isostasy is the corresponding state of balance which exists between extensive blocks of the earth's crust, which rise to different levels and appear at the surface as mountain ranges, widespread plateaus, or plains. The idea implies that there is a certain minimum level below the surface, where the pressure due to the weight of the material in each unit column of the crust is everywhere the same. This *isopiestic* (uniform pressure) level may be regarded as the base of the crust or lithosphere. The earth's major relief is said to be *compensated* by the differences of density within the crust, and the level where the compensation is complete, *i.e.* the isopiestic level, is often referred to as the *level of compensation*. Naturally, individual peaks and valleys are not separately balanced in this way ; the minor relief features of the surface are easily maintained by the strength of the crustal rocks. As pointed out on p. 33

perfect isostasy is rarely attained, though there is generally a remarkably close approach.

If a mountain range were simply a protuberance of rock resting on the continental platform and wholly supported by the strength of the foundation, then a plumb line—such as is used for levelling surveying instruments—would be deflected from the true vertical by an amount proportional to the gravitational attraction of the mass of the mountain range. The first hint that mountains are not merely masses stuck on
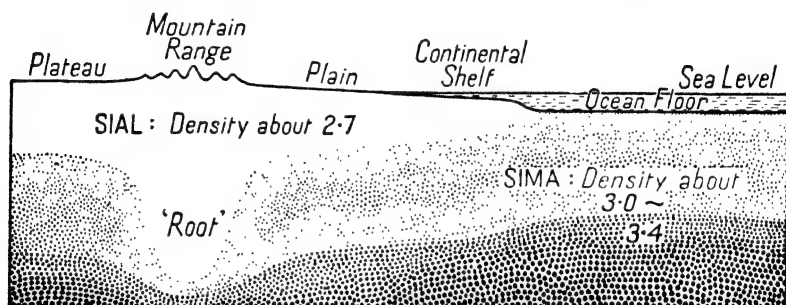
Fig. 4
Diagrammatic section through the earth's crust to illustrate the relationship between surface features and the probable distribution of sial and sima in depth. Based on gravity determinations and exploration of the crustal layers by earthquake waves

the crust was provided by the Peru expedition of 1735. Bouguer found that the deflection of the plumb line by the Andes was surprisingly small, and he expressed his suspicion that the gravitational attraction of the Andes " is much smaller than that to be expected from the mass represented by these mountains." Similar discrepancies were met with during the survey of the Indian lowlands south of the Himalayas. The attraction of the enormous mass of Tibet and the Himalayas was estimated to be sufficient to deflect the plumb line by at least 15 seconds of arc, but the real deflection found by Everest was only 5 seconds of arc. Even more remarkable was the observation that along the south coast of the Bay of Biscay the plumb line was actually deflected towards the Bay instead of towards the Pyrenees.

Only one physical explanation of these discrepancies is available. There must be a deficiency of mass in the crustal columns underlying the visible mountain ranges, *i.e.* the density of the rocks must be relatively low down to considerable depths. The possible density distributions are, of course, infinite. Fortunately, we know something of the rocks within the crust and can say what the probable densities are. Moreover, earthquake waves can be used to explore the depths (see page 371), and evidence from this source indicates that mountain ranges have sialic roots going down to depths of 40 km. or more ; that under plains near sea level the thickness of the sial is only 10 or 12 km. ; and that beneath the ocean floor the sial is either absent or quite thin. Fig. 4 illustrates an approximation to the structure of the crust in relation to the surface relief.

The Distribution of Land and Sea

Certain peculiarities in the distribution of land and sea have aroused discussion ever since the main features of the earth's surface were discovered.

1. The marked concentration of land in the northern hemisphere and of water in the southern, combined with a reversal of this contrast in the polar regions.

2. The occurrence of 81 per cent. of all the land in the "land hemisphere," which has its pole in Brittany and includes North America, Europe, Asia, and Africa and more than half of South America ; and the predominance of water in the corresponding "water hemisphere," which has its pole near New Zealand. The following figures bring out these differences :

	Percentage of land
"Land hemisphere" . . .	49
Northern hemisphere . . .	39
Whole earth	29
Southern hemisphere . . .	19
"Water hemisphere" . . .	9

3. The southerly extension of the three continental blocks of South America, Africa, and Australia.

4. The antipodal relation between land and sea. 44·6 per cent. of the surface has sea opposite sea, but only 1·4 per cent. has land opposite land. 95 per cent. of the land is antipodal to sea.

The so-called Tetrahedral hypothesis—now abandoned—was an ingenious attempt to " explain " points 1, 3, and 4. A tetrahedron is a three-dimensional figure bounded by four
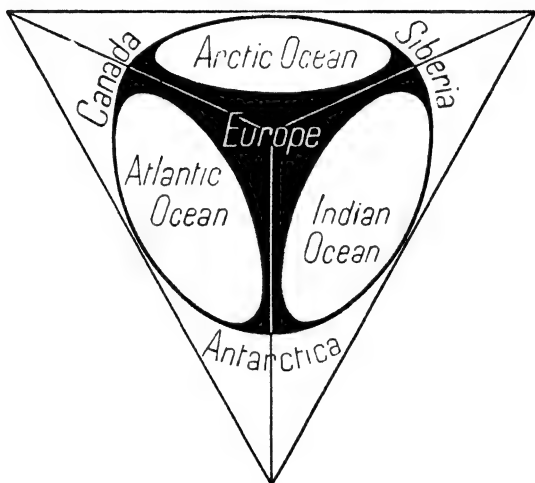
FIG. 5
To illustrate the " tetrahedral " distribution of continents and oceans

equilateral triangular faces, like a three-sided pyramid with a triangular base. Since, for a given surface area, a sphere is the regular figure with the greatest volume, while the tetrahedron is the regular figure with the smallest volume, it was thought that a contracting globe would tend to shrink towards a tetrahedral form. Thus, regarding the earth as a contracting globe, the ocean depressions would—on this view—be produced by an irregular collapse of the crust on a shrinking interior ; the Pacific, Indian, Atlantic, and Arctic oceans corresponding to the four tetrahedral faces, while the continents would be left as the elevated regions containing the

edges and corners (Fig. 5). It is true that the present-day pattern of land and sea is crudely simulated by a " tetrahedron" mounted on an apex representing the South Pole, though it should be noticed that the tetrahedron has to have one face—corresponding to the Pacific—very much larger than the others.

A fatal objection to the tetrahedral hypothesis is that an earth with a homogeneous crust could never have contracted towards a tetrahedral form, the reason being that any approach to a tetrahedron in a body with the mass of the earth would be gravitationally unstable and inconsistent with isostasy. The weight of the upstanding edges and corners (if they ever developed) would be so great that they would sink in again until the stable form of a globe was restored. A very small globe could contract to a form resembling a tetrahedron ; an enormous one, like the earth, could not.

Now we have already seen that the continents are essentially rafts of light sial, surrounded by ocean floors of heavy sima. It is for this reason that the continents stand high above the ocean floors. But mere collapse of the crust on a shrinking interior could not possibly have changed the chemical and mineral composition of the crust so that the rocks of the tetrahedral edges and corners became light enough to continue to stand up, or those of the faces so heavy that they would stay depressed. Thus we see that contraction could not account for the distribution of the continents without also accounting for the distribution of the sial, and this it cannot do.

Our problem is thus carried a stage further back, to that of the rafts of sial that constitute the continents. The material of the sial may be regarded as a kind of light slag which accumulated at the surface during the earth's consolidation from a molten state. We should expect it to have accumulated uniformly, so that it would everywhere form the upper layer of the crust. Where, then, is the sialic material that is missing from the ocean floors ? Obviously, it must be either in the earth or outside the earth, and speculative answers have been based on each of these alternatives.

If part of the sial was removed from the earth, the moon is the most probable place to look for it. The moon probably

separated from the earth at a very early stage in the history of our planet. If a sial shell had already formed before the moon was born, much of it must have been carried away when the great rupture occurred. Long ago it was suggested that the vast Pacific basin might be a relic of the scar that was left behind, and it has since been discovered that this is by far the greatest of the regions from which a cover of sial is lacking. This hypothesis is an attractive one, but unfortunately it has to meet the great difficulty that the moon could only have separated while the parent planet was still in a molten state, *i.e.* before there could have been a sial shell. By the time the sial had formed the interior would almost certainly have become too stiff for separation of the moon to be mechanically possible.

If the missing sial is still in the crust, it must be concentrated
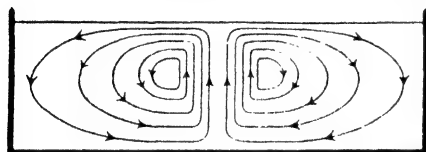
Fig. 6
Convection currents in a layer of liquid uniformly heated from below

in the continental rafts. A clue as to how such a concentration might be brought about is provided by observing the behaviour of the light scum on the surface of jam which is gently boiling. The heat from below keeps the jam slowly circulating (Fig. 6). A hot current ascends near the middle, and turning along at the surface, it sweeps the scum to the edges, where the current descends. The scum is too light to be carried down, and so it accumulates until it is skimmed off. When the earth was molten it would cool by means of similar circulations. Convection currents would rise in certain places, spread out horizontally, and then turn down again. There are reasons, as we shall see in later chapters, for suspecting that a subcrustal circulation may still be going on within the earth, though now at an excessively slow rate. However, when the circulation was vigorous, the horizontal currents spreading out from each ascending current may have swept certain regions clear of sial. These would become ocean basins. Where the

horizontal currents of one convecting system met those of a neighbouring system they would be obliged to turn down, and the light sial would thus become concentrated in the regions overlying the descending currents. These regions would become continents. The " convection current " hypothesis is plausible, but as yet it is no more than an intelligent guess. The origin of the continents remains an unsolved geological problem.

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CHAPTER III

THE CHANGING FACE OF THE EARTH

WEATHERING, EROSION, AND DENUDATION

THE circulations of matter that are continually going on in the zones of air and water, and even of life, constitute a very complicated mechanism which is maintained, essentially, by the heat from the sun. A familiar example of such a circulation is that of the winds. Another, more complex, is the circulation of water. Heat from the sun lifts water vapour from the surface of oceans, seas, lakes, and rivers, and wind distributes the vapour far and wide through the lower levels of the atmosphere. Clouds are formed, rain and snow are precipitated, and on the land these gather into rivers and glaciers. Finally, most of the water is returned to the oceanic and other reservoirs from which it came (Fig. 7). These circulations are responsible for an important group of geological processes, for the agents involved—wind, rain, rivers, and glaciers—act on the land by breaking up the rocks and so producing rock-waste which is gradually carried away.

Part of every shower of rain sinks into the soil and promotes the work of decay by solution and by loosening the particles. Every frost shatters the rocks with its expanding wedges of freezing water (Plate 4A). Life also co-operates in the work of destruction. The roots of trees grow down into cracks, and assist in splitting up the rocks (Plate 4B). Worms and other burrowing animals bring up the finer particles of soil to the surface, where they fall a ready prey to wind and rain. The soil is a phase through which much of the rock-waste of the lands must pass before it is ultimately removed. The production of rock-waste by these various agents, partly by mechanical breaking and partly by solution and chemical decay, is described as *weathering*.

Sooner or later the products of weathering are removed from their place of formation. Blowing over the lands the

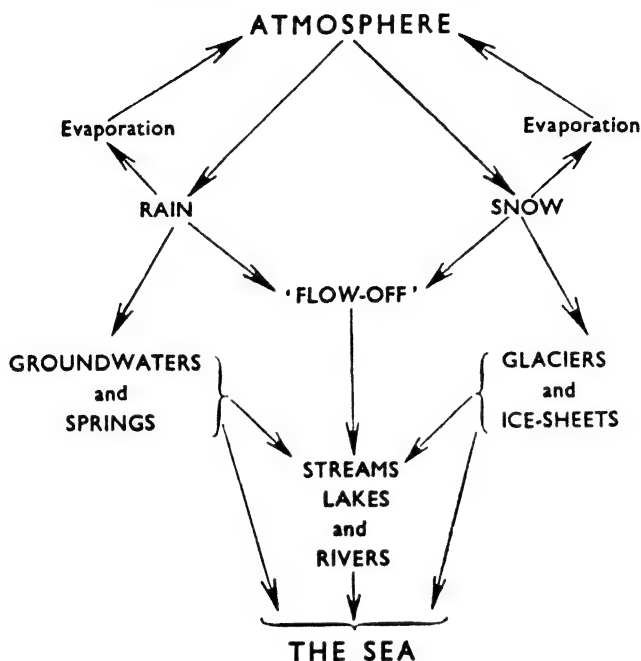



FIG. 7

The circulation of meteoric water. Part of the water which ascends from the depths by way of volcanoes reaches the surface for the first time ; such water is called *juvenile* water to distinguish it from the *meteoric* water already present in the hydrosphere and atmosphere

winds pick up dust and sand and carry them far and wide. Glaciers grind down the rocks over which they pass during their slow descent from ice-fields and high mountain valleys. Rainwash and landslips feed the rivers with fragments, large and small, and these are not only carried away, but are used by the rivers as tools to excavate their floors and sides. And in addition to their visible burden of mud and sand, the river waters carry an invisible load of dissolved material, extracted from rocks and soils by the solvent action of rain and soil water, and by that of the river water itself. Winds, rivers, and glaciers, the agents that carry away the products of rock-waste, are known as transporting agents. All the destructive

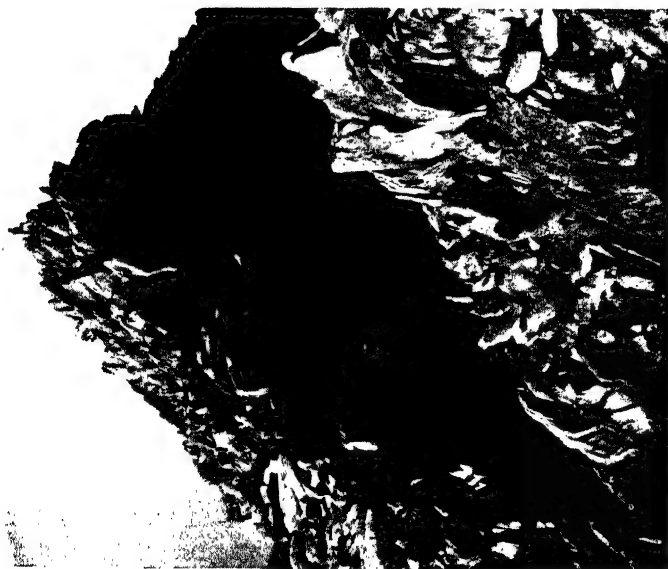
processes due to the effects of the transporting agents are described as *erosion* (L. *erodere*, to gnaw away).

It is convenient to regard weathering as rock decay by agents involving little or no transport of the resulting products, and erosion as land destruction by agents which simultaneously remove the debris. Both sets of processes co-operate in wearing away the land surface, and their combined effects are described by the term *denudation* (L. *denudo*, I make bare).

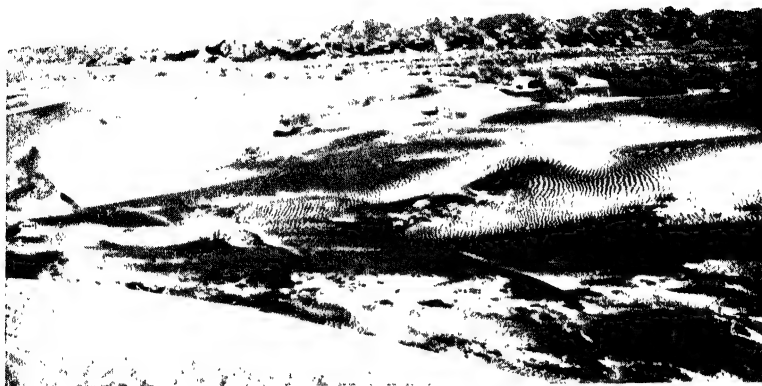
Deposition of Sediment

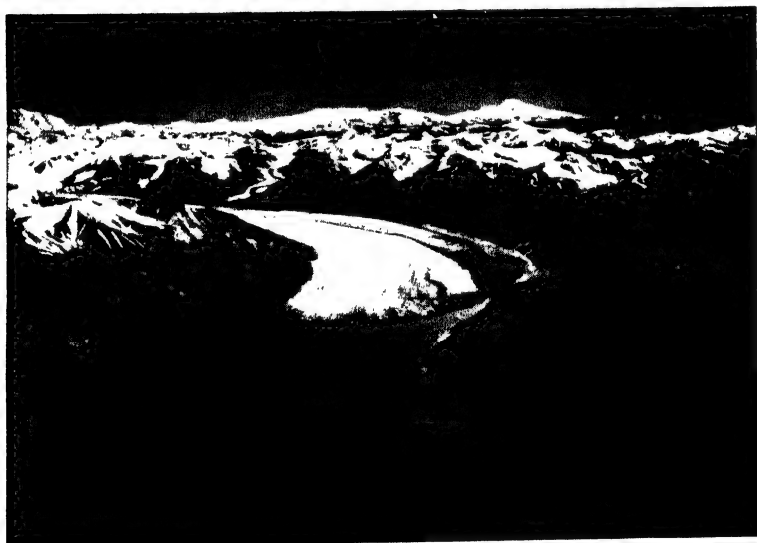
The sediment carried away by the transporting agents is sooner or later deposited again. Sand blown by the wind collects into sand dunes along the seashore or in the desert (Plate 5A). Where glaciers melt away, the debris gathered up during their journey is dumped down anyhow (Plate 5B), to be dealt with later by rivers or the sea. When a stream enters a lake the current is checked and the load of sand and mud gradually settles to the bottom. Downstream in the open valley sand and mud are spread over the alluvial flats during floods, while the main stream continues, by way of estuary or delta, to sweep the bulk of the material into the sea. Storm waves thundering against rocky coasts provide still more rock-waste, and the whole supply is sorted out and widely distributed by waves and currents. Smooth and rounded water-worn boulders collect beneath the cliffs. Sandy beaches accumulate in quiet bays. Out on the sea floor the finer particles are deposited as broad fringes of sediment, the finest material of all being swept far across the continental shelves, and even over the edge towards the deeper ocean floor, before it finally comes to rest. All these deposits are examples of sedimentary rocks in the making.

We have still to trace what happens to the invisible load of dissolved mineral matter that is removed from the land by rivers. Some rivers flow into lakes that have no outlet save by evaporation into the air above them. The waters of such lakes rapidly become salt because, as the famous astronomer

[*G. P. Abraham Ltd., Keswick*

(A) Frost-shattering of Ordovician igneous rocks, North Peak of Tryfan, N Wales

Crown Copyright Reserved] [*H.M. Geol. Survey*

(B) Ice-transported boulder, with crack enlarged by the growth of tree roots, Trefarthen, Anglesey

[*W. C. Mendenhall, U.S. Geol. Survey*

(A) Sand dunes in the Colorado Desert, Imperial Co., California

[*U.S. Geol. Survey*

(B) Terminal and lateral moraines deposited by the Chisana Glacier, Alaska

Halley realized more than two centuries ago, " the saline particles brought in by the rivers remain behind, while the fresh evaporate." Gradually the lake waters become saturated and rock salt and other saline deposits, like those on the shores and floor of the Dead Sea, are precipitated. Most rivers, however, reach the sea and pour into it the greater part of the material dissolved from the land. So, as Halley pointed out, " the ocean itself is become salt from the same cause." But while, on balance, the salinity of the sea is slowly increasing, much of the mineral matter contributed to the sea is taken out again by living organisms. Cockles and mussels, sea-urchins and corals, and many other sea creatures, make shells for themselves out of calcium carbonate abstracted from the water in which they live. When the creatures die, most of their soft parts are eaten and the rest decays. But their hard parts remain, and these accumulate as the shell banks of shallow seas, the coral reefs of tropical coasts and islands, and the grey globigerina ooze of the deep-sea floor. All of these are limestones in the making. Life, as a builder of organic sediments, is a geological agent of first importance.

The Importance of Time

It will now be realized that while the higher regions of the earth's crust are constantly wasting away, the lower levels are just as steadily being built up. Evidently denudation and deposition are great levelling processes. In the course of a single lifetime their effects may not be everywhere perceptible. Nevertheless they are not too slow to be measured. About half an inch has already been worn from the outer surface of the Portland stone with which St. Paul's Cathedral was built two centuries ago. Britain as a whole is wasting away rather faster—at an average rate of about one foot in three or four thousand years. At this rate a million years would suffice to reduce the varied landscapes of our country to a monotonous plain. Evidently slowly acting causes are competent to produce enormous changes if only they continue to operate through sufficiently long periods.

Now, geologically speaking, a million years is a comparatively short time, just as a million miles is a short distance from an astronomical point of view. One of the modern triumphs of geology and physics is the demonstration that the age of the earth cannot be much less than 2,000 million years (p. 105). Geological processes act very slowly, but geological time is inconceivably long. The effects of slow processes acting for long periods have been fully adequate to account for all the successive transformations of landscape that the earth has witnessed.

Earth Movements

It follows that there has been ample time, since land and sea came into existence, for Britain, and indeed for the highest land areas, to have been worn down to sea level over and over again. How then does it happen that every continent still has its highlands and mountain peaks? The special creation theory, immortalized in the words:

> "When Britain first at Heaven's command
> Arose from out the azure main,"

is not very helpful, yet it does suggest a possible answer. The lands, together with adjoining parts of the sea floor, may have been uplifted from time to time. Alternatively, the level of the sea may have fallen, leaving the land relatively upraised. In either case there would again be land well above the sea, and on its surface the agents of denudation would begin afresh their work of sculpturing the land into hills and valleys. An additional factor is the building of new land—like the volcanic islands that rise from oceanic depths—by the accumulated products of volcanic eruptions. Each of these processes of land renewal has repeatedly operated in the course of the earth's long history, but it is the first—the movement of the crust itself—which has most commonly and most effectively rejuvenated the lands and compensated for their recurrent wastage.

Relative movements between land and sea are convincingly

proved by the presence in Islay and Jura, and in many other places, of typical sea beaches, now raised far above the reach of the waves (Plate 6). Behind these raised beaches the corresponding cliffs, often tunnelled with sea caves, are still preserved. In Scandinavia and Peru old strand lines can be traced which rise from near sea level in the south to heights of hundreds of feet in the north. Such tilting of the shores shows that the movements involve actual upheaval of the crust and not merely withdrawal of the sea. The former uplift of old sea floors can be recognized in the Pennines, where the grey limestones contain fossil shells and corals that bear silent witness to the fact that the rocks forming the hills of northern England once lay under the sea. The most spectacular example of uplift is provided by Mount Everest, the summit of which is carved out of sediments that were originally deposited on the sea floor of a former age.

When earth movements take place suddenly they are recognized by the passage of earthquake waves. In certain restless belts of the crust, for example in Japan, there may be several shocks every day, occasionally with terribly disastrous consequences. Exceptionally, as in Alaska, upward jerks of more than forty feet have been observed, but usually the movements are on a smaller scale.

If crustal movements were all vertical, then uplifted beds of sediment from the sea floor would generally be found lying in nearly horizontal positions. So, indeed, they often are, but in many places they have been corrugated and buckled into folds (Plate 7) in much the same way as a tablecloth wrinkles up when it is pushed along the table. The layers of rock seen in the cliffs and on the rocky foreshores of parts of Devon and Berwickshire have been folded tightly together, like the pleats of a closed concertina. If the tablecloth is pushed along still further after a fold has appeared, the fold will gradually turn over and overlap the flat part that is being pushed along. So also in the rocks. In many an Alpine precipice great sheets of rock are visibly " overfolded " in just the same way, so that parts of them now lie upside down (see Plate 81).

Such amazing structures as these show that certain parts of the earth's crust have yielded to horizontal compressive forces of unimaginable intensity. All the great mountain ranges of the world are carved out of rocks that have been folded and crumpled and overthrust. Long belts of the crust have been so squeezed and thickened that they had no alternative but to rise to mountainous heights.

The crustal movements have not always and everywhere been upwards. That parts of the land surface have recently subsided is proved by the local occurrence around our shores of *submerged forests* uncovered only at the lowest tides. But there seems never to have been a time when all the lands were submerged at once. Earth movements and volcanic additions to the surface have evidently been fully competent to restore the balance of land and sea whenever that balance has been threatened by the levelling processes of denudation. Most of the sediments originally deposited on the shallow sea floor, sometimes hardened and cemented into firm and durable rocks, sometimes bent and twisted into intricate folds, sometimes accompanied by lavas and volcanic ashes, have sooner or later been upheaved to form new lands.

Volcanic and Igneous Activity

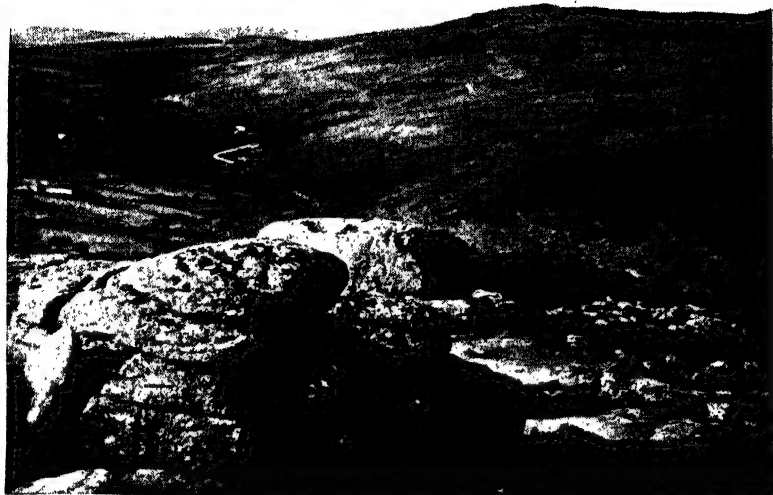
Earth movements are not the only manifestations of the earth's internal activities. Volcanic eruptions provide a most spectacular proof that the earth's interior is so hot that locally even the crustal rocks pass into a molten state. A volcano is essentially a rift or vent through which *magma* (molten rock material highly charged with gases) from the depths is erupted at the surface as flows of lava or as explosive clouds of gases and volcanic ashes. Magma may reach the surface through long fissures, from which lavas spread over the surrounding country, filling up the valleys and forming widespread volcanic plains or plateaus. In the more familiar volcanoes the magma ascends through a central pipe, around which the lavas and ashes accumulate to form a more or less conical volcanic

[*Fox Photos Ltd.*

FIG. 8

Dartmoor: a large granite intrusion now exposed by denudation and carved into a landscape of hills and valleys

mountain. Thus volcanic activity is a constructive process whereby new materials are brought to the surface, and new topographic forms built up.

Volcanic activity is only the surface manifestation of the movement through the earth's crust of magma generated in the substratum or in exceptionally heated regions of the crust itself. The new rocks formed in the crust from magma that failed to reach the surface are called *intrusive* rocks, to distinguish them from lavas, which are called volcanic or *extrusive* rocks. In many places intrusive rocks are exposed to observation, as on Dartmoor, as a result of the removal of the original cover by denudation (Fig. 8). All rocks which owe their origin to the solidification of magmas in depth (intrusive rocks) or of lavas at the surface (extrusive rocks) are described as *igneous* rocks (L. *ignis*, fire). This definition of igneous rocks is, however, not quite complete (see page 67).

Metamorphism of Rocks

When crustal rocks come under the influence of (*a*) the intense pressure or stress accompanying severe earth movements; (*b*) the increased temperature associated with igneous activity; or (*c*) chemically active gases and liquids from magmatic sources, they respond by changes in structure and mineral composition, and so become transformed into new types of rocks. All such changes are described as *metamorphism*, and examples of them will be considered in the following chapter. Here the term is introduced to draw attention to the fact that rocks respond to the earth's internal activities not only by crumpling or by fusion, but also by recrystallization. It must be carefully noticed that metamorphism is the very antithesis of weathering. Both processes bring about great changes in pre-existing rocks, but weathering is destructive while metamorphism is constructive. Instead of reducing a pre-existing rock to a decaying mass of rock-waste and soil, metamorphism brings about its transformation, often from a dull and uninteresting-looking stone, into a crystalline rock of bright and shining minerals and attractive appearance.

Summary of the Geological Processes

It will now be clear from our rapid survey of the leading geological processes that they fall into two contrasted groups. The first group—denudation and deposition—includes the processes which act on the crust at or very near its surface, as a result of the movements and chemical activities of air, water, ice, and living organisms. Such processes are essentially of external origin. The second group—earth movements, igneous activity and metamorphism—includes the processes which act within or through the crust, as a result of the physical and chemical activities of the material of the substratum and of magmas formed in or passing through the crust. Such processes are essentially of internal origin.

Both groups of processes operate under the control of gravitation (including attractions due to the sun and moon), co-operating with the earth's bodily movements—rotation about its axis and revolution around the sun. But if these were all, the earth's surface would soon reach a state of approximate equilibrium from which no further changes of geological

CLASSIFICATION OF GEOLOGICAL PROCESSES

I. Processes of External Origin

1. *Denudation* (Weathering, Erosion, and Transport)
   Sculpturing of the land surface and removal of the products of rock decay mechanically and in solution

2. *Deposition*
   (*a*) of the debris transported mechanically (*e.g.* sand and mud)
   (*b*) of the materials transported in solution :
      (i) by evaporation and chemical precipitation (*e.g.* rock salt)
      (ii) by the intervention of living organisms (*e.g.* coral limestone)
   (*c*) of organic matter, largely the remains of vegetation (*e.g.* peat)

II. Processes of Internal Origin

1. *Earth Movements* (including Earthquakes)
   Uplift and depression of land areas and sea floors ; and mountain building by lateral compression (folding and overthrusting) of rocks

2. *Igneous Activity*
   The intrusion of magmas and the extrusion of lavas and other volcanic products

3. *Metamorphism*
   The transformation of pre-existing rocks into new types by the action of heat, pressure, stress, and chemically active migrating fluids.

significance could develop. Each group of processes, to be kept going, requires some additional source of energy. The processes of external origin are specifically maintained by the radiation of heat from the sun. Those of internal origin are similarly maintained by the liberation of heat from the stores of energy locked within the earth.

Throughout the ages the face of the earth has been changing its expression. At times its features have been flat and monotonous. At others—as to-day—they have been bold and vigorous. But in the long struggle for supremacy between the sun-born forces of land destruction and the earth-born forces of land renewal, neither has permanently gained the mastery.

Isostasy and Geological Processes

It will now be realized that geological processes bring about changes that must inevitably upset the ideal state of isostatic balance which gravitation tends to establish. When a mountain range is carved into peaks and valleys and gradually worn down by the agents of denudation, the load on the underlying column of the crust is reduced by the weight of the rock-waste that has been carried away. At the same time a neighbouring column, underlying a region of delta and sea floor where the rock-waste is being deposited, receives a corresponding increase of load. Unless a complementary transfer of material occurs in depth, the two columns cannot remain in isostatic equilibrium. At the base of the crust the pressure exerted by the loaded column is increased, while that exerted by the unloaded column is decreased. In response to this pressure difference in the substratum a slow flowage of material is set up, as illustrated in Fig. 9. The loaded column sinks and the unloaded one rises. This process, whereby isostasy is restored, is called *isostatic readjustment.*

The upper part of the substratum consists of hot rock material which probably differs from the crystalline rocks seen at the surface by being much richer in gases. Acting like molecular ball-bearings, the gases facilitate flowage, but

[H.M. Geol. Survey

(A) 25-foot raised beach, with sea cave in the quartzite cliff behind, Loch Tarbert, Jura

[H.M. Geol. Survey

(B) 100-foot raised beach, west of Rhuvaal Lighthouse, Islay

RAISED SHORE LINES

PLATE 7

Folded Jurassic strata, the Stair Hole, west of Lulworth Cove, Dorset [*F. N. Ashcroft*

nevertheless the movement is extremely sluggish. Moreover, in some regions it appears that the substratum material is not altogether devoid of strength. It then behaves as a plastic substance (with a little strength) rather than as a viscous substance (with no strength). In this case no flowage is possible

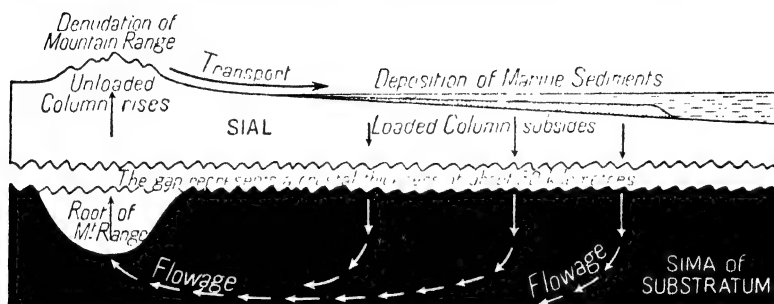



Fig. 9

Section illustrating isostatic readjustment in response to denudation and deposition

until the departure from isostasy is sufficient to set up a pressure difference that can overcome the strength. The region concerned will therefore remain slightly out of isostatic balance. In practice, perfect isostasy is rarely attained, though there is generally a remarkably close approach.

It may happen that certain processes disturb the pre-existing isostatic balance much more rapidly than it can be restored by deep-seated flowage in the substratum. For example, when the thick European and North American ice-sheets began to melt away towards the end of the Ice Age, about 25,000 years ago, these regions were quickly relieved of an immense load of ice. The resulting uplifts which then began are still actively in progress. Far above the shores of Finland and Scandinavia there are raised beaches which show that a maximum uplift of nearly 900 feet has already occurred, and every twenty-eight years another foot is added to the total all around the northern end of the Gulf of Bothnia. The region is still out of isostatic balance, and it can be estimated that it has still to rise another 700 feet or so, before equilibrium can be reached.

A common misunderstanding about isostasy is that it is responsible for earth movements of all kinds. It must, therefore, be clearly realized that isostasy is only a state of balance; it is not a force or a geological agent. It is the disturbance of isostasy by denudation and deposition, earth movements and igneous activity, that brings into play the gravitational forces that restore isostasy. The restoration involves vertical movements of the crust which are additional to the earth movements brought about by the independent activities of the earth's interior.

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CHAPTER IV

MATERIALS OF THE EARTH'S CRUST : MINERALS

ELEMENTS AND CRYSTALS

THE vast majority of rocks are aggregates of minerals. Of the remainder, some, like pumice, are made of volcanic glass, while others, like coal, are composed of the products of organic decay. All these ingredients in turn are made of atoms of the chemical elements. Although ninety-four different elements are now known, nine of these are so abundant that they make up more than 99 per cent. of all the many thousands of rocks that have been analysed. Many of the others, such as gold, tin, and copper, though extremely rare in ordinary rocks, are locally concentrated in ore deposits that can be profitably worked.

AVERAGE COMPOSITION OF CRUSTAL ROCKS

(After Clarke and Washington)

IN TERMS OF ELEMENTS			IN TERMS OF OXIDES		
Name	*Symbol*	*Per cent.*	*Name*	*Formula*	*Per cent.*
Oxygen	O	46·71	Silica	SiO_2	59·07
Silicon	Si	27·69	Alumina	Al_2O_3	15·22
Aluminium	Al	8·07	Iron oxides *	Fe'''_2O_3	3·10 } 6·81
Iron	Fe	5·05		$Fe''O$	3·71 }
Calcium	Ca	3·65	Lime	CaO	5·10
Sodium	Na	2·75	Soda	Na_2O	3·71
Potassium	K	2·58	Potash	K_2O	3·11
Magnesium	Mg	2·08	Magnesia	MgO	3·45
Titanium	Ti	0·62	Titania	TiO_2	1·03
Hydrogen	H	0·14	Water	H_2O	1·30
		99·34			98·80

Some of the elements, *e.g.* gold, copper, sulphur, and carbon (as diamond and graphite), make minerals by them-

* It should be noticed that iron makes two kinds of oxides, distinguished as ferrous oxide, FeO, and ferric oxide, Fe_2O_3. If it is desired to discriminate between the two corresponding states in which iron can exist, ferrous iron is represented by Fe'' and ferric iron by Fe'''.

selves, but most minerals are compounds of two or more elements. Oxygen is by far the most abundant element in rocks. In combination with other elements it forms compounds called oxides, some of which occur as minerals. As silicon is the most abundant element after oxygen, it is not surprising that silica, the oxide of silicon, SiO_2, should be the most abundant of all oxides. Silica is familiar as quartz, a common mineral which is specially characteristic of granites, sandstones, and quartz veins. The formula, SiO_2, is a simple way of expressing the fact that for every atom of silicon in quartz there are two atoms of oxygen. Quartz has, therefore, a perfectly definite composition. The formulæ for other oxides and compounds of other types may be similarly interpreted.

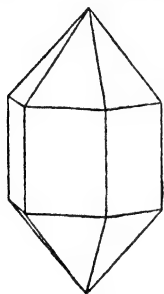



Fig. 10
Doubly terminated crystal of quartz

In the cavities of mineral veins quartz can be found as clear transparent prisms, each with six sides and each terminated by a pyramid with six faces (Fig. 10). The old Greeks gave the name crystal (*krustallos*, clear ice) to these beautiful forms, and to this day water-clear quartz is still known as rock crystal (Fig. 11). Most other minerals and a great variety of chemically prepared substances can also develop into symmetrical forms bounded by flat faces, and all of these are now called *crystals*. It is an old joke in the world of crystallography that the beauty of a crystal depends on the planeness of its faces. In recent years the study of crystals by means of X-rays has revealed the fact that the symmetrical shape is simply the outward expression of a perfectly organized internal structure. The atoms of which a crystal is composed are arranged in an orderly fashion, the different kinds of atoms being built into a definite pattern which is repeated over and over again, as in the design of a wallpaper, except that in crystals the design is in three dimensions.

Every crystalline chemical compound has a characteristic unit-pattern, and as the different kinds of atoms are present in definite proportions, it follows that the crystals of any given

[*British Museum (Natural History*)

FIG. 11

Group of quartz crystals from Minas Geraes, Brazil

compound have a definite and constant composition. It sometimes happens, however, that two (or more) related compounds may have the same atomic pattern ; they are then said to be *isomorphous*. In isomorphous compounds the atoms of certain related elements are interchangeable in the crystal edifice, just as bricks of different colours can be built into a wall without altering either the structure of the wall or its outward shape. In " mixed " crystals of this kind the composition is therefore not constant, but ranges between certain definite limits.

In non-crystalline, or *amorphous*, substances the atoms are arranged haphazardly, like the bricks in a tumbled heap. Examples of such substances are glass, opal, and limonite. Only a few non-crystalline substances are regarded, by common usage, as minerals, and these are generally distinguished as *mineraloids*. Apart from these, all minerals are naturally occurring inorganic crystalline substances, each of which has its own specific variety of crystal structure ; the chemical composition may be constant (as in quartz) or it

may vary (as in the felspars) within limits that depend on the degree to which the atoms of certain elements can substitute for those of other elements without changing the specific pattern of the atomic framework.

Rock-forming Minerals

Although about 2,000 minerals are known, most common rocks can be adequately described in terms of a dozen or so, as the following table indicates. It is, therefore, well worth while to become familiar with these essential rock-forming minerals, and especially to learn something of their chemical compositions. An attempt is made here to present this minimum equipment of chemical knowledge as briefly as possible.

AVERAGE MINERAL COMPOSITIONS OF SOME COMMON ROCKS

Minerals	Igneous Rocks		Sedimentary Rocks		
	Granite	Basalt	Sandstone	Shale	Limestone
Quartz	31·3	—	69·8	31·9	3·7
Felspars	52·3	46·2	8·4	17·6	2·2
Micas	11·5	—	1·2	18·4	—
Clay minerals	—	—	6·9	10·0	1·0
Chlorite	—	—	1·1	6·4	—
Hornblende	2·4	—	—	—	—
Augite	rare	36·9	—	—	—
Olivine	—	7·6	—	—	—
Calcite and dolomite	—	—	10·6	7·9	92·8
Iron ores	2·0	6·5	1·7	5·4	0·1
Other minerals	0·5	2·8	0·3	2·4	0·3

The student should refer to textbooks for additional information, and above all he should handle typical specimens of minerals and rocks and examine actual rock exposures out of doors whenever opportunity affords.

The following are the chief examples of oxide minerals :

Quartz, SiO_2, already referred to above.

Hæmatite, Fe'''_2O_3	All important ores of iron. Magnetite is often
Magnetite, $Fe''O.Fe'''_2O_3$ or Fe_3O_4	associated with *Ilmenite*, $FeO.TiO_2$, especially
Limonite, $Fe'''_2O_3.H_2O$	in basalts and rocks of similar composition

Ice, crystalline water, H_2O, the mineral of which glaciers and ice sheets are composed

Silica combines with one or more of the other common oxides to form a group of extremely important rock-forming minerals called silicates. The most abundant of the silicate minerals are the *felspars*, nearly all of which are built up of the three compounds :

Alkali felspars { *Orthoclase*, *Or*, $KAlSi_3O_8$
Albite, *Ab*, $NaAlSi_3O_8$ } *Plagioclase*
Anorthite, *An*, $CaAl_2Si_2O_8$ } *Plagioclase*

In the *Alkali felspars* the compounds *Or* and *Ab* are combined in limited proportions, Na and K being interchangeable to a limited degree in the crystal structure. Thus the mineral *Orthoclase*, the most familiar of the alkali felspars, generally contains a small amount of albite. Albite and anorthite, however, are perfectly isomorphous (that is, they can combine in all proportions), thus forming a continuous series of minerals, known collectively as *plagioclase*. In this case the atomic group (NaSi) is interchangeable in the crystal structure with the atomic group (CaAl). The formulae for albite and anorthite can be written in a way that makes clear the possibility of this substitution :

Plagioclase { *Albite* $Al(NaSi)Si_2O_8$
Anorthite $Al(CaAl)Si_2O_8$.

When albite is more abundant than anorthite the felspar is called sodic or soda plagioclase. Varieties with anorthite in excess are distinguished as calcic or lime plagioclase.

Orthoclase can be easily recognized as the cream, pink, or grey mineral in granite. In some granites, like those of Cornwall or Shap (Fig. 12), large slab-like crystals of orthoclase, an

inch or more in length, are sprinkled through the rock. When the crystals are broken across, the surfaces are smooth and glistening. Orthoclase does not break just anyhow ; it "cleaves" along parallel cleavage planes in the crystal structure across which cohesion is comparatively weak. Just as in many wall-papers the repetition of the unit pattern gives rise to a parallel series of "open" lines, so in the atomic pattern of a crystal there may be similar "open" planes, and it is along these

[*G. S. Sweeting*

FIG. 12

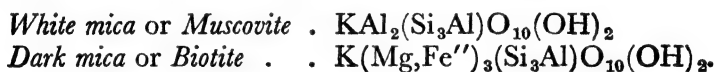
A polished surface of Shap granite, showing large crystals of orthoclase embedded in a ground-mass of finer grain. The resulting pattern is described as *porphyritic texture*, p. 45

that the crystal splits most readily. Orthoclase has two such sets of cleavage planes, and the mineral takes its name from the fact that they are exactly at right angles (Gr. *orthos*, rectangular ; *clastos*, breaking). Plagioclase has also two cleavages, but in this case, though nearly at right angles, they are not exactly so. Hence the name (*plagios*, oblique).

When any of the felspars are decomposed (*e.g.* by weathering or other processes involving addition of water), the usual residual products are either (*a*) a very fine-grained variety of

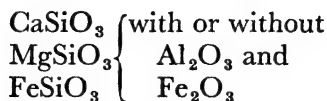
white mica (see below) called *sericite*, or (*b*) a *clay mineral*, of which there are several varieties. Most of the clay minerals are hydrous silicates of aluminium, with formulæ such as $Al_4Si_4O_{10}(OH)_8$ or $Al_4Si_4O_6(OH)_{16}$, but some varieties (as in fuller's earth) contain a little magnesium in addition. Under certain conditions in tropical climates all the silica may be removed from felspars by weathering. The residue then left is *bauxite*, a mixture of two aluminous minerals with the compositions $Al_2O_3.H_2O$ and $Al_2O_3.3H_2O$. Bauxite is of great value as the only workable ore of aluminium.

Quartz and felspars (orthoclase and sodic plagioclase) are the characteristic minerals of the sialic rocks, together with micas, of which there are two leading varieties :

White mica or *Muscovite* . $KAl_2(Si_3Al)O_{10}(OH)_2$
Dark mica or *Biotite* . . $K(Mg,Fe'')_3(Si_3Al)O_{10}(OH)_2$.

The expression (Mg, Fe″) in the formula for biotite means that Mg and Fe″ are interchangeable in the atomic structure of the crystals. Similarly, Al and Fe‴ are interchangeable, and fluorine (F) may take the place of some of the (OH). Biotite has therefore a considerable range of composition, and the formula given is merely illustrative of the possibilities. Micas all have a perfect cleavage, because their atoms are arranged in parallel layers, and splitting between the layers is very much easier than tearing across them. Cleavage flakes of mica are both flexible and elastic. From certain exceptionally coarse varieties of granite, sheets of mica can be obtained which are large enough to be used for lamp chimneys and furnace windows.

Certain rocks of the kinds grouped together as sima (*e.g.* basalt) contain calcic plagioclase, but others are free from felspar. All of the sima rocks, however, are characterized by the abundance or predominance of heavy, greenish silicate minerals rich in magnesia and iron oxides, and therefore commonly known as ferromagnesian minerals. The leading ferromagnesian minerals are biotite, a group known as the *pyroxenes*, a group known as the *amphiboles*, and *olivine*.

The common pyroxenes may be regarded as built up of compounds such as

$$\left.\begin{matrix} CaSiO_3 \\ MgSiO_3 \\ FeSiO_3 \end{matrix}\right\} \begin{matrix} \text{with or without} \\ Al_2O_3 \text{ and} \\ Fe_2O_3 \end{matrix}$$

The chief non-aluminous pyroxene is

Diopside . . . $Ca(Mg,Fe)(Si_2O_6)$

The chief aluminous pyroxene, and by far the commonest member of the group, is

Augite . . . $Ca(Mg,Fe,Al)(Si,Al)_2O_6$

The amphiboles are somewhat similar in their range of composition, the most essential difference being the presence of (OH) which, as in mica, may be partly replaced by fluorine (F). The commonest member of the group is

Hornblende . . . $(Ca,Mg,Fe)_4(Si,Al)_4O_{11}(OH)$

Augite and hornblende are readily distinguished by their crystal forms and cleavages. Both minerals have two well developed cleavages ; but in augite the angle of intersection between the cleavage planes is nearly 90°, whereas in hornblende it is nearer 60° or 120°.

Olivine is of simpler composition, its formula being $(Mg,Fe)_2SiO_4$. The mineral is familiar as the transparent bottle-green crystals cut as gem stones under the name *peridot.* Rocks in which olivine is the most abundant mineral (generally in association with other ferromagnesian minerals) are called peridotite. Nearly all the heavier rocks of the sima group are peridotites ; the term " sima " obviously reflects the chemical composition of olivine and its ferromagnesian associates.

By a process of alteration involving addition of water, olivine is changed to *serpentine,* $(Mg,Fe)_6Si_4O_{10}(OH)_8$; the same name is given to rocks formed from peridotites by similar alteration. The corresponding alteration products of the ferromagnesian minerals which contain alumina and iron

oxides are green, fine-grained, flaky minerals known collectively as *chlorite*.

Carbon (C), though not listed in the table on page 35, is only a little less abundant than hydrogen. It forms an enormous number of compounds, mainly with hydrogen and oxygen. Some of these are the chief constituents of living organisms, fuels (wood, peat, coal, and oil), and the organic matter of soils. Carbon dioxide, CO_2, is an important atmospheric gas. Many forms of vegetation abstract it from the air or from natural waters which hold it in solution, and the supply is restored partly by CO_2 liberated during breathing, organic decay, and the burning of fuels, and partly by CO_2 given off during volcanic eruptions. CO_2 combines with many other oxides, forming carbonates, some of which occur as minerals. The most important of these are :

Carbonate rock-forming minerals:
- *Calcite* $CaCO_3$, the predominant mineral of limestones
- *Dolomite* $CaCO_3.MgCO_3$, occurring in a carbonate rock, which is itself called dolomite
- *Chalybite* or *Siderite* $FeCO_3$, an important iron ore

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Chapter V

MATERIALS OF THE EARTH'S CRUST: COMMON ROCKS

The few references to rocks that have already been made suffice to show that rocks may be divided into three major groups—igneous, sedimentary, and metamorphic—according to the processes that were concerned in their origin.

IGNEOUS ROCKS

Granite

In its natural home, granite may be examined in the tors and valleys of many a rough moor (Figs. 8 and 62), or in the quarries where it is wrought for its durability and handsome appearance as a building stone. In most towns it can be seen as hewn blocks or decorative slabs and columns.

Granite is a coarse-grained rock composed essentially of quartz, felspar, and mica. In some examples (*e.g.* from Aberdeen) the interlocking minerals are uniformly distributed, and all are about the same size. Felspar, mostly orthoclase, is the most abundant mineral. Gleaming plates of mica (black or bronze-like biotite, accompanied in some varieties by silvery white muscovite) can easily be recognised. Between the felspars and micas the remaining spaces are occupied by translucent, glassy-looking quartz.

Instead of being uniformly granular, certain granites (*e.g.* from Cornwall and Shap Fells, Fig. 12) have a distinctive pattern or *texture*, clearly seen on polished slabs, due to the development of orthoclase as conspicuous, isolated crystals which are much larger than those of the granular ground-mass in which they are embedded. This texture is technically described as *porphyritic*, a term derived from an old Greek

[*L. Hawkes*

FIG. 13

Basalt pierced by granophyre (a fine-grained variety of granite), shore N. of mouth of Hvaldal, N. of Lon Fjord, south-east Iceland

word meaning "purple." The Romans, prospecting for decorative stones in Egypt two thousand years ago, came upon a deep purple rock—which they called *porphyrites lapis*—of such attractive appearance that they actively quarried it for columns, vases, and slabs. In the course of time the same name came to be applied to other rocks which contain large crystals embedded in a finer ground-mass, even though they lack the purple hue of the original porphyritic rock.

The problem whether granite crystallized from solution in water, or from a hot molten state, aroused fierce controversy in the early days of geology. The most influential advocate of the first view was Werner, of Saxony, who taught his students that granite was the oldest of rocks, and that it was precipitated from a primæval ocean that he supposed to have covered the whole globe. The second view was first advanced by Hutton, of Edinburgh, who discovered that granite veins from some of the Scottish granites penetrated the adjoining rocks. Hutton thus realised that granite had been intruded

into still older rocks, and he naturally inferred that it must have been in a liquid state when it did so (Fig. 13). Moreover, he found that the rocks in contact with granite had been baked and thereby metamorphosed, very much as clay is altered when it is fired and "metamorphosed" into brick. Evidently, then, the granites he investigated had crystallized not only from a liquid, but from an intensely hot liquid; that is to say, from a molten or magmatic state.

BASALT

Basalt is a dark-coloured, very fine-grained rock, which is of widespread occurrence as lava flows of all geological ages. Its igneous origin is therefore not in doubt. Nevertheless, like granite, basalt was also the subject of an early controversy. Some varieties of basalt contract on cooling in such a way that the rock cracks into long polygonal columns, most of which are six-sided, and set at right angles to the base of the flow. The well-known columns of the Giant's Causeway in Antrim and of Fingal's Cave in Staffa (Plate 3) are beautifully developed examples of this natural masonry. In Saxony similar columnar basalt occurs in isolated patches, capping the hills. Now Werner, adopting the general opinion of his day, believed that the basaltic columns were gigantic crystals. He also believed that crystals could only grow from aqueous solutions. From these two erroneous ideas he drew the conclusion that basalt must be a chemical precipitate from his imaginary world-wide ocean. In this case, Werner's mistake was corrected in France. The Puys of Auvergne are a group of extinct volcanoes, with cones, craters, and lava flows still perfectly preserved. Here Desmarest found a sheet of black columnar basalt, underlain by cindery lava and burnt soil. He traced the basalt across country until it finally led him up to the crater of one of the Puys. No further proof was needed that the basalt had been erupted from the volcano as a lava flow.

The early geologists found it extremely difficult to in-

vestigate fine-grained rocks like basalt, for with the limited means at their disposal they were rarely able to identify the tiny crystals in such compact materials. In 1851 this difficulty was overcome by Sorby, a Sheffield metallurgist, who showed how a slice of rock could be ground down to a film so thin (about 1/1000th inch) that it became transparent, thus making it possible, after mounting the film on a glass slide, to view

[*G. O'Neill*

FIG. 14
Photomicrograph of a thin section of basalt, showing plagioclase (*white*), augite (*grey*), and ilmenite (*black*) × 50

the rock through a microscope, and so to examine the magnified minerals with ease.

A thin section of basalt prepared in this way has the appearance illustrated in Fig. 14. Lath-like crystals of a clear colourless mineral, which is calcic plagioclase, form an irregular open network which extends throughout the rock. The grey mineral, which is greenish or brownish as seen through the microscope, is augite. Many basalts also contain olivine, sometimes abundantly. The black opaque mineral is magnetite or ilmenite. It is the high proportion of iron in basalt which is

responsible for the dark colour of the rock, and for the rusty-looking material (limonite) that encrusts its surface when it has been exposed to the weather.

Basalt is not always wholly made up of crystals. Varieties that solidified very rapidly, as a result of sudden chilling, had no time to crystallize completely. In consequence, the part that remained uncrystallized had no alternative but to solidify into black volcanic glass. Crystals may already have grown in the magma before its eruption as lava. In this case the resulting basalt is a porphyritic variety, with relatively large crystals in a very fine-grained or glassy ground-mass. At the top of a basalt flow the lava may be blown into a cinder-like froth by the expansion of escaping gases. Even in the more compact basalts, gas-blown cavities of various sizes may occur. These may be empty ; or lined with crystals, often beautifully developed ; or even completely filled with minerals. The filled " bubbles " sometimes look like almonds, and so the name *amygdale* is given to them (from the Greek *amygdalos*, an almond). Basalts which are studded with numerous amygdales are called *amygdaloidal* basalts. One of the commonest minerals found in amygdales is *agate*, banded in concentric layers of different tints. Agate is a variety of silica, and sometimes, inside a lining of agate, crystals of quartz or of amethyst (purple quartz) may be found projecting into the hollow space within.

Classification of the Common Igneous Rocks

Granite and basalt, and types closely related to them, are by far the most abundant of the igneous rocks. Granite is an example of the coarse-grained rocks that crystallized slowly in large masses within the crust. Such rocks are described as *plutonic*, after Pluto, the god of the underworld. Basalt, on the other hand, is an example of the very fine-grained or glassy rocks that cooled quickly from lavas that flowed over the surface. These are *volcanic* rocks, after Vulcan, the god of fire. Between the two extremes there are rocks of intermediate grain

that cooled and crystallized at intermediate rates, generally in small intrusions like the dykes and sills described on page 83. Such rocks are distinguished as *hypabyssal* (intermediate depths). Many of the hypabyssal rocks of sialic composition are remarkable for a very conspicuous development of porphyritic texture, in consequence of which they are known by the familiar rock name *porphyry*.

The simple relationship between mode of occurrence and grain size indicated above does not completely cover all the possibilities, because (*a*) the outer skin of a thin dyke or sill may be chilled against cold wall-rocks almost as quickly as the upper layers of a lava flow against the air ; and (*b*) the rate of cooling in the interior of a thick lava flow may be as slow as it is within the smaller dykes and sills. However, provided that such inevitable exceptions to the general rule are not forgotten, the following correlations serve as a useful basis for the classification of igneous rocks :

MODE OF OCCURRENCE			TEXTURE	
Extrusive	Lava flows	*Volcanic*	Glassy Very fine-grained	and porphyritic varieties of each
Intrusive	Minor intrusions	Hypabyssal	Fine-grained	
	Major intrusions	PLUTONIC	Coarse-grained	

According to this scheme, the rocks of any given composition may have any one of eight different textures. In the case of rocks of granitic composition, the eight textural types are distinguished by the following names :

Volcanic	*Glassy*	*Obsidian and Pumice* (frothy)	*Porphyritic Obsidian*
	Stony	*Rhyolite*	*Porphyritic Rhyolite*
Hypabyssal		Felsite	Quartz-porphyry
PLUTONIC		GRANITE	PORPHYRITIC GRANITE

In the case of rocks of basaltic composition, the corresponding types are *tachylyte* (the glassy form of basalt), *basalt*, dolerite or diabase (the common rock of many dykes and sills, much used for road metal), and GABBRO, together with porphyritic varieties of each.

Igneous rocks are also classified according to the kinds and

proportions of their constituent minerals. Many of the rocks commonly referred to as "granite" have more plagioclase than orthoclase and are therefore not true granites; it is convenient to distinguish them by the name granodiorite, because they are intermediate in mineral composition between granite and quartz-diorite. Diorite, with little or no quartz, is made up essentially of plagioclase and hornblende. Many large "granite" masses, consisting mainly of granite and granodiorite, pass marginally into quartz-diorite and diorite.

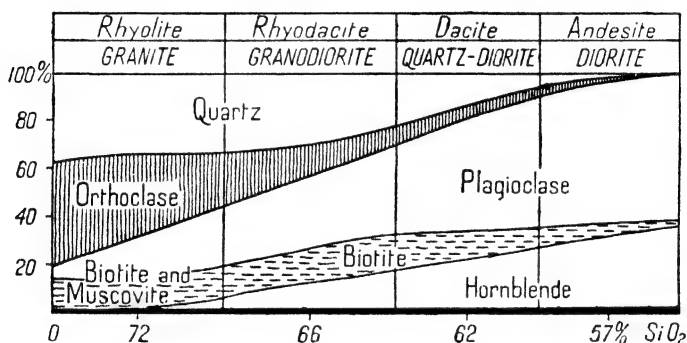



FIG. 15

Variation in mineral composition and silica content of the rock series granite-diorite. Accessory minerals in black (at the base)

The continuous mineral variation, and the conventional dividing lines between the types, are shown graphically in Fig. 15.

As this example indicates, igneous rocks can be classified mineralogically, and therefore identified, by means of criteria such as:

(*a*) the presence or absence of quartz

(*b*) the kinds of felspar and the proportions between them (and in some cases by the absence of felspar), and

(*c*) the kinds of ferromagnesian (F.M.) minerals.

MINERALOGICAL CLASSIFICATION OF THE CHIEF IGNEOUS ROCKS

Volcanic or *very fine-grained* types in *italics*
Hypabyssal or fine-grained types in ordinary type
PLUTONIC or COARSE-GRAINED types in CAPITALS

	Orthoclase > than Sodic Plagioclase	Sodic Plagioclase > than Orthoclase	Sodic Plagioclase predominant	
Quartz essential F.M. Biotite or Hornblende or both	*Rhyolite* Quartz-porphyry GRANITE	*Rhyodacite* Granodiorite-porphyry GRANODIORITE	*Dacite* Quartz-porphyrite QUARTZ-DIORITE	
	Orthoclase predominant	Orthoclase and Plagioclase roughly equal	Sodic Plagioclase predominant	No Felspar
Little or no Quartz F.M. Hornblende and/or Biotite and/or Augite	*Trachyte* Porphyry SYENITE	*Trachyandesite* Monzonite-porphyry MONZONITE	*Andesite* Porphyrite DIORITE	HORNBLENDITE
			Calcic Plagioclase predominant	No Felspar
Little or no Quartz F.M. Augite and Iron Ores			*Basalt* Dolerite or Diabase GABBRO	PYROXENITE
No Quartz F.M. Augite, Olivine, and Iron Ores			*Olivine-basalt* Ol.-dolerite or Ol.-diabase OLIVINE-GABBRO	PERIDOTITE

SEDIMENTARY ROCKS

Sandstone and Shale

Sandstone is perhaps the most familiar of all rocks, for it is easily quarried, and it is used more than any other kind of stone for building purposes. Examined closely, using a lens if necessary, a piece of sandstone is seen to consist of grains

[*G. S. Sweeting*

Fig. 16
Photomicrograph of sandstone, Torridon Sandstone, North-West Highlands of Scotland × 30

of sand identical in appearance with those that are churned up by the waves breaking on a beach. Most of the grains consist of more or less rounded grains of quartz, but there are others of cloudy, weathered-looking felspar, and generally a few shining spangles of mica can be seen (Fig. 16).

Clearly, sandstone is made of second-hand materials, of worn fragments derived from the disintegration of some older rock, such as granite, which contained the same minerals. It

differs from deposits of modern sands only in being coherent instead of loose. Calcite is a common cementing material. Brown sandstones are cemented by limonite and red varieties by hæmatite. In pure white, extremely hard sandstones, the cement is quartz. These materials were deposited between the grains by ground-waters which percolated through the sand when it was buried under later sheets of sand or other formations.

In the steep face of a quarry or cliff, successive beds or layers can be seen, differing from one another by variations in colour or coarseness of grain (Plate 8A). At intervals there may be strongly marked bedding planes, along which the sandstone is easily split, due perhaps to the presence of a thin layer packed with flat-lying flakes of mica, or to the intervention of a thin band of clay or shale. Evidently the beds or strata have been formed by the deposition of layer after layer of sediment.

Along the beach, and especially near the cliffs, boulders and pebbles are heaped up by storm waves. Then come the sands, and beyond them on the sea floor lie still finer deposits of mud, made up of the tiniest grains of quartz and altered felspar, shreds of mica, and minute flaky particles of clay minerals. Each of these different types can be recognized among the stratified rocks. Sooner or later, a sheet of sandstone thins out and passes laterally into clay or shale. Traced in the other direction, it may become coarser in grain and pass into a massive boulder bed or conglomerate (see Plate 21B). The term *conglomerate* is applied to cemented fragmental rocks containing rounded fragments such as pebbles ; if the fragments are angular or sub-angular, the rock is called *breccia.*

The very fine-grained sedimentary rocks, corresponding to mud, are described as clay, mudstone, or shale. Mudstone is compact, but shale can easily be divided into thin laminæ. This fissility is due to a structure resembling stratification on a fine scale, which is distinguished by the term *lamination.* The micas and clay minerals all occur as minute films which lie with their flat surfaces parallel to the bedding, and in consequence the shale readily divides along the lamination planes.

Limestones

Limestones of suitable quality are widely used as building stones, because of the ease with which they can be worked, and some varieties, the aristocrats of a very mixed group, have become famous through their lavish use in great public buildings. Portland stone, for example, has been a favourite choice for many of London's greatest buildings, ever since Wren selected it for the rebuilding of St. Paul's Cathedral after the Great Fire of 1666. The towers and steeples of the London churches, the government offices in Whitehall, the front of Buckingham Palace, and most recently of all, the new home of London University, all display its use in varied styles of architecture.

The natural architecture of limestones can be studied in the quarries of Portland and the Cotswolds, in the grey scars of the Pennines (Plate 8B), and in the white gashes cut by lime-makers in the green slopes of the Chalk Downs. Some of the limestones of the Pennines are packed with the remains of corals and marine shells, and the bead-like relics of the stems of sea-lilies (animals like starfishes on long stalks—Plate 9A). The yellow Cotswold limestones, more open and porous, are often crowded with fossil shells, while belemnites, looking like thick blunt pencils, and the coiled forms of ammonites add further interest and variety (see Fig. 50). The fine-grained and friable limestone known as chalk contains smooth white shells and sea urchins. But besides these visible fossils there are innumerable little coiled or globular shells which can be seen only by microscopic examination ; these are exactly like the foraminifera dredged up from the deep-sea floor, where globigerina ooze is collecting at the present day (see Plate 72).

Evidently many limestones are accumulations of organic remains, vast cemeteries in which the teeming life of the sea has been entombed. It is easy to prove with dilute acid that shells and corals and limestones are all composed of calcium carbonate. They effervesce briskly when the acid is applied

and give off carbon dioxide, while a drop of the resulting solution held on a clean platinum wire in the flame of a bunsen burner colours the flame with the brick-red tint due to calcium. Soft-bodied organisms abstracted the calcium carbonate from sea water and deposited it around or within themselves, to form a protective covering or a supporting framework.

The limestones of Portland and Bath also contain shells, but they are mainly composed of rounded grains that look like

[*G. S. Sweeting*

FIG. 17
Photomicrograph of oolitic limestone, Farley, Bath
× 30

insects' eggs. For this reason they are called oolites or oolitic limestones (Greek *oon*, an egg). Under the microscope each granule is found to be made of concentric layers of calcium carbonate, often with a bit of shell at the centre (Fig. 17). Along coral strands, where the conditions are favourable, oolitic grains are forming to-day around such nuclei by the deposition of calcium carbonate from sea water. Rolled about by the surf, the grains tend to grow equally on all sides, and so to become round.

Limestones are thus seen to be deposits formed from dis-

[*R. Welch*

(A) Bedding and jointing in Carboniferous sandstone, Muckross Head, Co. Donegal

[*H.M. Geol. Survey*

(B) The Great Scar Limestone (Carboniferous) above Malham Cove, Yorkshire

PLATE 9

[W. H. Watts

(A) Weathered surface of crinoidal limestone (Carboniferous), Flintshire

[S. H. Reynolds

(B) Limestone in the making: a deposit of shell-gravel (mainly cockles)

solved material : generally, but not always, from sea water. They usually accumulate outside the stretches of sand and mud that in most places border the lands, but where the sea is uncontaminated by muddy sediment, and especially where the cliffs themselves happen to be made of older limestones, they may form close up to the land. Beaches may locally be composed of sand made up, not of quartz grains, but of shell debris (Plate 9B). Similarly, the sands associated with coral reefs and atolls consist largely of coral debris, ground down by the waves.

Many limestones are distinctly fragmental, whether formed from organic remains or from oolitic grains. Others are extremely fine-grained and compact, and most of these represent chemical precipitates from waters rich in calcium carbonate. The double carbonate of calcium and magnesium (dolomite) may also be precipitated ; either directly, or by the action of warm sea water on limestone already in process of accumulation on the floor of the sea. In these ways *magnesian* or *dolomitic limestones*, grading into pure *dolomite rocks*, have been formed. Dolomite was selected as the building stone for the Houses of Parliament. Unfortunately, the sulphurous fumes from the neighbouring potteries of Lambeth corroded the delicate carvings of the structure, turning the magnesia of the stone into easily soluble epsom salts. Dolomite, however, may be an excellent building stone where it is not exposed to such abnormal weathering conditions.

METAMORPHIC ROCKS

Marble and Crystalline Limestones

Limestones are known commercially as " marble " when they can be effectively polished and used for decorative purposes. Corals and the stems of sea-lilies give a variegated pattern commonly seen on polished slabs cut from the grey limestones of the Pennines. The pink and grey limestones of Torquay have been fissured by earth movements, and per-

[*E. J. Garwood*

FIG. 18

Metamorphism of Carboniferous limestone by the Great Whin Sill, Falcon Clints, Teesdale, Co. Durham

meating solutions have mottled the stone in tints of red and filled the cracks with white veins of calcite. This example illustrates the ease with which limestone becomes changed by natural processes into " marbles " of endless variety. Limestone is chemically a very sensitive rock, and the walls of many of Lyons' restaurants show in spectacular fashion how readily it has responded to the effects of heat, pressure and percolating waters.

To the geologist, however, the term marble is restricted to limestones which have been completely recrystallized by metamorphic processes during their burial in the earth's crust. Under the influence of heat from igneous intrusions the calcium carbonate of shells and finer particles alike is gradually reconstructed into crystals of calcite of roughly uniform size. All traces of fossils are destroyed, and the rock, when pure, becomes a white granular rock like the well-known statuary marble from Carrara in Italy. The great sheets of basalt in

Antrim lie over a surface of Chalk (Plate 17A), and the chalk, instead of being soft and friable like that of southern England, has become hard and indurated by the heat from the overlying lavas. And against the channels through which the lava reached the surface, the chalk is transformed locally into saccharoidal marble.

It may be asked how it is that carbon dioxide did not escape under such conditions, as it does when limestone is heated to make lime. The explanation is that when the heating takes place under pressure, as when the limestone is confined under a load of overlying rocks, the carbon dioxide is not liberated as a stream of gas, but only as dispersed molecules, temporarily freed. These mobile molecules may be thought of as acting like tiny ball-bearings, lubricating the rock during the recrystallization of its minerals. Conditions favourable to marble formation were successfully imitated in 1805 by Sir James Hall, an eminent friend of Hutton's, who tested many of the rival theories around which controversy was then raging by devising experimental methods of attacking the problems. Hall enclosed pounded chalk in a porcelain tube, which in turn was fitted closely into a cylindrical hole bored in a solid block of iron, and securely sealed at the open end. On heating this " bomb " to the highest temperature at his command, the chalk was transformed into a fine granular marble.

When the original limestone is not pure, but contains other carbonate minerals such as dolomite, and impurities of sand or clay, various chemical reactions take place between the ingredients when they are heated up sufficiently. New minerals are then developed, olivine and garnet being examples, and the carbon dioxide thus liberated is driven off :

$$\underset{\textit{Dolomite}}{2CaMg(CO_3)_2} + \underset{\textit{Quartz}}{SiO_2} = \underset{\textit{Olivine}}{Mg_2SiO_4} + \underset{\textit{Calcite}}{2CaCO_3} + \underset{\textit{Carbon dioxide}}{2CO_2}$$

Moreover, when a limestone or dolomite is invaded by granitic or other magmas, part of the magmatic material may diffuse into the surrounding rock, thus adding new constituents and so causing the growth of still other types of new minerals. The beautiful green serpentine-marble of Connemara, familiar to

all who have visited Ireland, probably originated in this way. In some localities in the United States and Sweden important masses of iron ore have been formed at the expense of limestone. Evidently magmatic fluids rich in iron migrated into the limestones, leaving the iron there as black magnetite, and carrying off in solution the replaced calcium carbonate.

Slate

The world-famous roofing slates that are quarried from the rugged hills around Snowdon owe their value to a structure whereby they can be split along planes that are not parallel to the bedding, like the lamination of shales, but inclined to

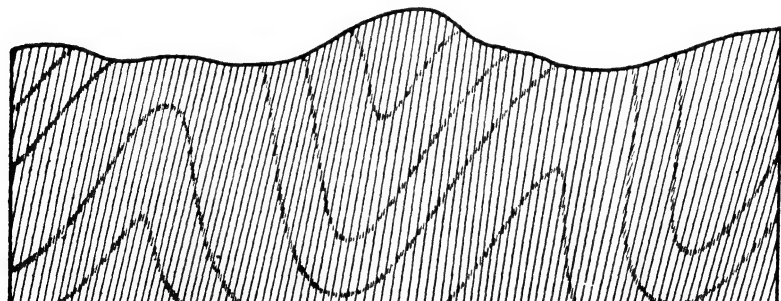



Fig. 19
To illustrate the relation of slaty cleavage to bedding

it, often at a high angle. This structure is neither stratification nor lamination, but a fissility or cleavage, often of great perfection. It is distinguished as *slaty cleavage* (Fig. 19). It must not be confused with the cleavage of crystals, for the latter is a property depending on the orderly arrangement of atoms, whereas slaty cleavage depends on the orderly arrangement of minute flaky minerals such as mica, clay, and chlorite within the rock. A thin section of slate cut at right angles to the cleavage shows all the flaky minerals lying parallel to the cleavage planes. It is due to this orientation that the rock splits along these planes and along no others.

Traces of the original bedding planes can be made out in the quarry face wherever bands of contrasted colour or more gritty material are present; such bands are often badly crumpled and contorted. If, by a rare chance, a fossil is found, it, too, is deformed and squeezed out of shape. Clearly an overpowering pressure has been exerted on the rock, and observation shows that it must have been applied sideways. Lateral earth-pressure, sufficiently intense to crumple the rocks in most intricate fashion, has compressed a thick mass of compact mudstone or laminated shale so that the flat surfaces of all the flaky minerals shifted round into positions approximately at right angles to the direction from which the pressure came.

In 1856 Sorby demonstrated the truth of this explanation by experimenting with a stiff mixture of clay and tiny flakes of iron ore. The flakes orientated themselves with their flat surfaces perpendicular to the direction of the pressure. Tyndall later developed cleavage in wax by pressure. In this case the new structure was due to the flattening out of the original globular particles of wax. So we find that slates may also be made out of certain very fine-grained materials even if they contained no flaky minerals to begin with. The silvery green slates of the Lake District have been formed from beds of fine volcanic ashes. Their cleavage and silvery sheen is due, however, not merely to the flattening of the original particles, but also to the development of new minerals from the volcanic materials. Microscopically small shreds of mica and wisps of chlorite have grown in the rock, all with their film-like surfaces lying parallel to the cleavage direction.

Kinds of Metamorphism

Slate is thus an example of a rock on which a new " grain " has been impressed, mainly by the effect of shearing caused by severe compressional earth movements. To some extent chemical changes promoted by heat and solution have co-operated in facilitating the growth of new minerals. The

original shale or volcanic ash has responded by becoming a slate, a new type of rock. Since the main process is dynamic, slate is said to be a product of *dynamic metamorphism.*

The change from limestone to marble, on the other hand,

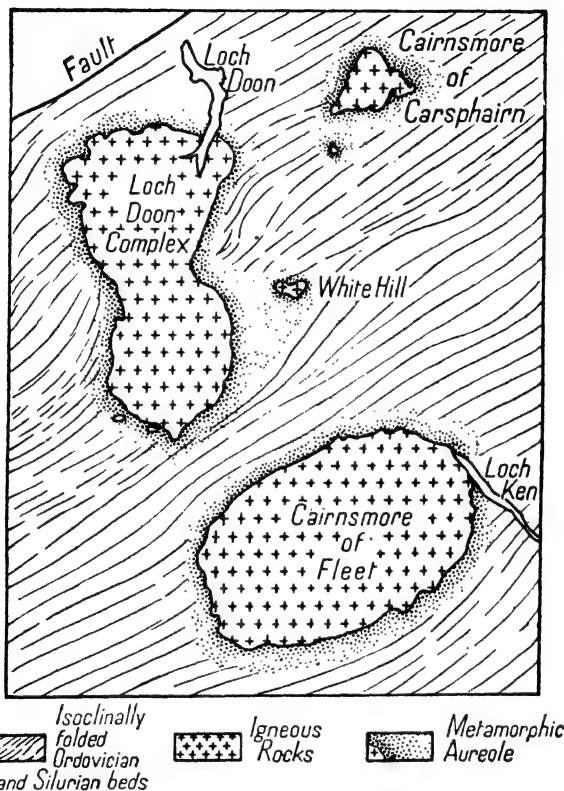



Fig. 20

Aureoles of contact metamorphism around small batholiths and stocks, Galloway, S.-W. Scotland

is mainly brought about by the action of heat. It illustrates the effects of *thermal metamorphism.* The rocks in contact with igneous intrusions are commonly metamorphosed by heat and migrating fluids, and metamorphism of this kind is distinguished as *contact metamorphism.* The zone of altered rock surrounding the intrusion is described as the metamorphic

aureole (Fig. 20). Where shales or slates are in contact with granite the mineral changes promoted by the rise of temperature become visibly conspicuous. Traced from the edge of the aureole towards the granite, the rocks begin to be variegated by little spongy spots which as yet are hardly individualized as definite minerals. Nearer the granite these commonly develop into a glistening felt of tiny brown and white flakes, which further on become larger, and can be recognized as micas. Close to the contact other new minerals may appear. Metamorphic rocks of this kind are called *hornfels* (plural, *hornfelses*).

When all the agencies of metamorphism operate together, as they do in the heated depths of a crustal belt where mountain building movements are in progress, the rocks throughout an extensive region are characteristically transformed, and the metamorphism is then described as *regional.*

Crystalline Schists

When shale or slate is recrystallized by regional metamorphism the effects of heat and migrating fluids lead to the development of mica and other new minerals on a visible scale, as in contact metamorphism. At the same time the effects of shearing or flowage give the rock a new structure, due to the stream-lined arrangement of the platy and elongated minerals. This structure is called *foliation,* a term based on its similarity to that of the tightly packed leaves of leaf-mould. Foliation may develop along an earlier cleavage, but more commonly it follows the stratification of sediments that have not been cleaved, and in some cases, when the shearing or flowage failed to coincide with the earlier parting planes, it follows a new direction altogether. The surfaces along which a foliated rock can be divided may be plane to undulating, wavy or contorted. When the foliation is closely spaced throughout the body of the rock, so that almost any part of it can be split into flakes or flat lenticles, the rock is called a *schist* (Gr. *schistos*, divided). The schistosity of the rock—that

is, the property whereby it can be easily split—is somewhat akin to slaty cleavage, but on a coarser, rougher, and less uniform scale.

Schists are named after the chief mineral responsible for the foliation in any given case. When this is mica, as frequently happens, the rock is called *mica-schist*, this being the type that develops from shales and slates. Another type is *hornblende-schist*, which develops from basaltic rocks, the hornblende being formed at the expense of the original augite. Sandstone and limestone rarely form schists, and then only crudely, the reason being that quartz and calcite are naturally granular minerals. The usual metamorphic equivalents of these rocks are quartzite and marble, respectively, both granulitic rocks.

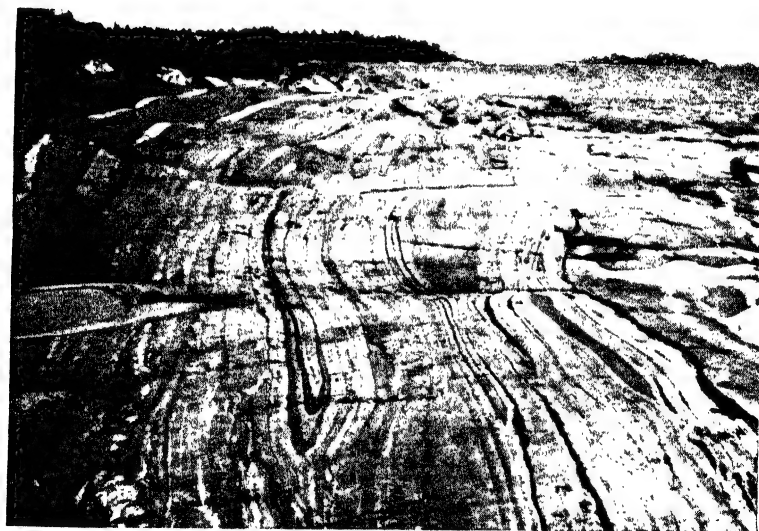
Gneisses and Migmatites

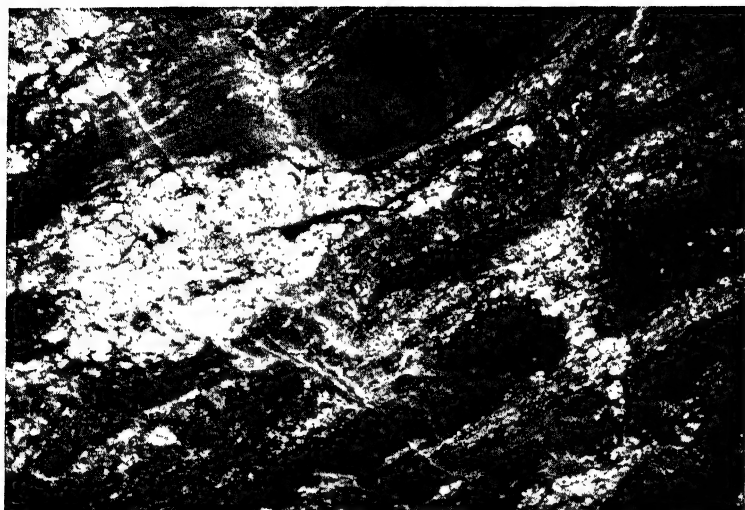
One of the most characteristic types of metamorphic rocks is that known by the old Saxon miners' term *gneiss*. Gneisses are found associated with schists and granites, particularly in regions where very ancient rocks are exposed. Like schist, gneiss is a foliated rock, but its foliation is open and interrupted. Highly micaceous layers alternate with bands or lenticles or " eyes " that are granular, and more like granite in their texture and composition. Many gneisses, indeed, have the mineral composition of granite or granodiorite, and thus they further differ from schists in containing felspar as an important mineral, especially in their granular portions.

Some gneisses may be simply the squeezed-out and recrystallized equivalents of granitic rocks, but most examples appear to represent transitions between schist and granite. If we examine areas where gneisses are well exposed, such as the low, wave-swept islands of southern Finland (Plate 10), we can see that the older schists seem to have been impregnated by granite in every conceivable way. In some places veins and tongues of granite magma appear to have run between the folia of the schists, like water seeping between the pages of a book. Close by, the schists are strewn with crystals of felspar

[C. E. Wegmann

(A) Hornblende-schists (dark) traversed by granite (light), Vantskar, Porto

[C. E. Wegmann

(B) Wave-swept surface of schists, migmatites, and granite veins, Borgå

SOUTH COAST OF FINLAND

[C. E. Wegmann

(A) Schists in various stages of replacement by granite, Hamnholmen, Porto

[C. E. Wegmann

(B) Folded schists almost completely granitized, Bodö, Pörtö

GRANITIZATION, SOUTH COAST OF FINLAND

(Plate 11A), again suggesting that granite magma soaked into the rocks. Such mixed gneisses are called *migmatites* (Gr. *migma*, a mixture). However, the first idea that migmatites result from the mixing of schist and granite magma cannot be sustained. Both the veined and the " eyed " varieties of migmatite pass into types with larger and more abundant felspars, so that the rock looks like a granite, except for a shadowy background representing vague remnants or "ghosts" of the original schists (Plate 11B). Finally, even the " ghosts " vanish, and only granite remains. The schists have somehow been transformed into granite. Where has the old material gone? Whence came the new and what was its composition? These are difficult questions, and they have not yet been fully answered. But clearly the problem of the origin of granite is not quite so simple as Hutton thought. Hutton read part of the story correctly, but we know to-day that it is no longer safe to assume that *all* granites and granodiorites crystallized from a completely molten state. In the alchemy of nature, migrating fluids from the depths soak into the schists, adding certain new ingredients and carrying away some of the old ones. As a result of this chemical interchange, the schists themselves are changed in composition, migmatites are formed, and the final product is a granitic rock. Moreover, there is growing evidence that locally the newly born granitic material became mobile and fluid. Consequently we have here a most important clue as to one—and perhaps the most important—of the ways in which granitic magmas have been generated.

The Cycle of Rock Change

According to the accepted theory that the earth was originally in a fluid state, the first rocks of the crust must inevitably have been igneous. However, none of these primordial rocks has ever been discovered. The oldest igneous rocks that can be found are seen to be intrusive into still older rocks which, though now metamorphic, were originally sedimentary. There must, of course, have been still older igneous rocks to

provide the materials of these sediments, and to serve as a foundation for their deposition, but such basement rocks appear to have vanished long ago in successive waves of fusion which attacked the crust from below. It is for this reason that no evidence of the earth's beginning has yet been detected. Hutton remarked a hundred and fifty years ago that he could find " no vestige of a beginning " and to-day, despite world-wide search, we are still obliged to say the same. All the

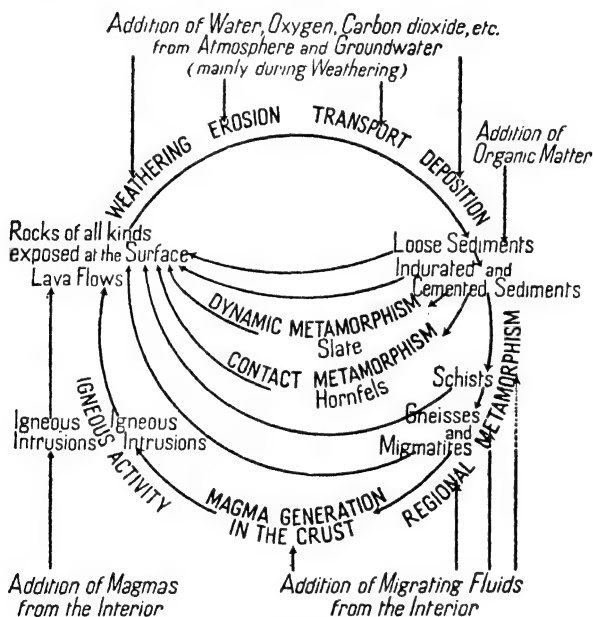



FIG. 21

The metamorphic cycle of rock change

observed igneous rocks have consolidated either from magmas that ascended from the depths, or (at least in part) from magmas that were generated within the crust by the fluxing action of heat and migrating fluids on the materials already there.

Sedimentary rocks are those produced by external processes from pre-existing rocks of all kinds, or from organic material derived mainly from air and water. Many of these

have remained undenuded and, together with the accumulated salts in the oceans, they represent the results of nearly 2,000 million years of surface activities. Others, however, have been deeply buried and metamorphosed.

Metamorphic rocks are those produced by internal processes on pre-existing rocks of all kinds, with the limitation that the rocks concerned remained essentially solid during their transformations. When the action of heat, stress, and migrating fluids became sufficiently intense, the rock materials became increasingly mobile, until they finally liquefied, wholly or in part. Thus, beyond a certain limit of intensity, metamorphism reaches the extreme stage—sometimes called ultrametamorphism—at which new magmas are generated. The rock formed by the subsequent consolidation of such magma can no longer be regarded as metamorphic. It has been re-born as an igneous rock, and the great cycle of rock change—igneous → sedimentary → metamorphic → igneous —is completed (Fig. 21).

In the light of the above considerations we can now attempt a more rigorous definition of an igneous rock. An igneous rock is one that has consolidated either (*a*) from magma ; or (*b*) from hot mobile material containing sufficient fluid to be capable of flow, in the course of which the pre-existing metamorphic structures are obliterated.

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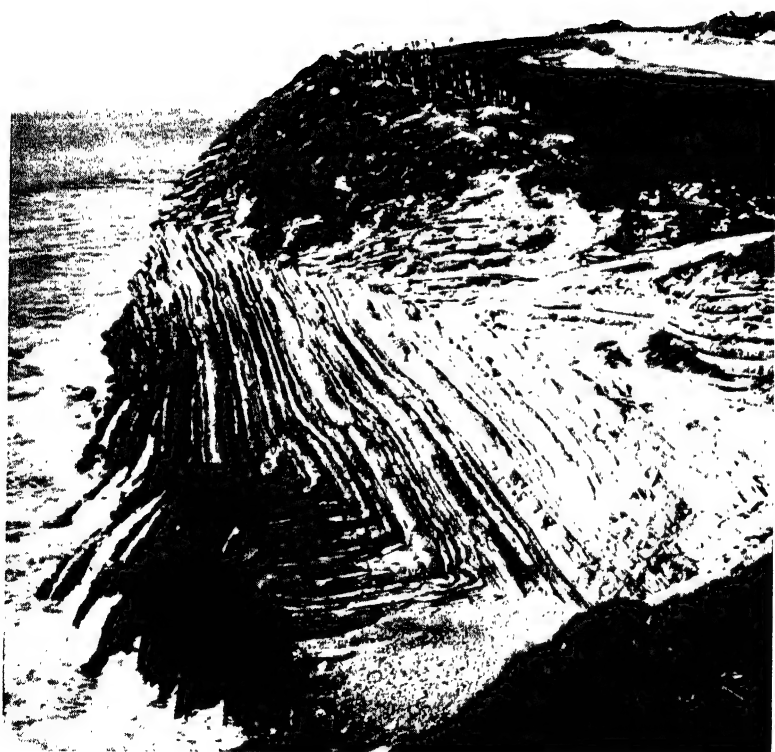
[*H.M. Geol. Survey*

(A) Anticline in Coal Measures, Sandersfoot, Pembrokeshire

[*H.M. Geol. Survey*

(B) Syncline in Coal Measures, North of Bude, Cornwall

PLATE 13

[*F. N. Ashcroft*

Sharp overfolds in the cliffs north of the harbour, St. Jean de Luz, Basses-Pyrénées, France

CHAPTER VI

ARCHITECTURAL FEATURES OF THE EARTH'S CRUST

FRACTURE, FLOWAGE, AND FLOW

ANY mass of rock in the earth's crust is subject to gravity and earth pressure. The resulting stresses can always be represented by three principal stresses acting mutually at right angles: P_1, the least (including tension); P_2, intermediate; and P_3, the greatest. One of the three is generally vertical and the other two horizontal (Fig. 22). If the maximum stress difference, $P_3 - P_1$, exceeds the strength of the rock, then the rock is strained, and it either breaks if it remains brittle, or suffers a change in shape or size if it becomes plastic. Near the surface, rocks yield mainly by fracture; but at greater depths, which vary according to the kind of rock, change of form takes place by solid flowage, that is, by plastic flow, the movements being facilitated by microscopic fractures and/or recrystallization.

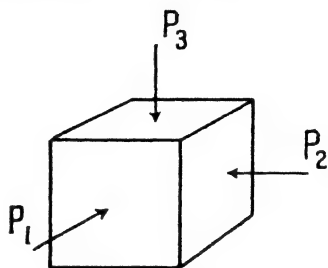



FIG. 22

Resolution of the stress conditions acting on a mass of rock into stresses acting along the three principal axes of stress, each of which is perpendicular to the other two

Thus for each kind of rock (under the given conditions of stress, temperature, and migrating fluids) there is a zone of flowage below a certain depth and a zone of fracture above it. A glacier illustrates the distinction very clearly. Here a superficial zone of fracture is demonstrated by the occurrence of crevasses in the ice. The glacier creeps down its valley, however, by flowage, and in a glacier the zone of flowage is quite near the surface, because ice, unlike ordinary rocks, is near its melting point, and recrystallization is easy.

When the ice of a glacier melts, the water flows away freely.

THE CHIEF STRUCTURAL RESULTS OF FRACTURE, FLOWAGE, AND FLOW

	Sedimentary	Metamorphic	Igneous
Fracture . . .	← Joints → Fractures along which practically no displacement of the rocks has occurred ← Faults → Fractures along which the rocks on one side have been displaced relatively to those on the other		
Fracture and Flowage . . .	← Folds → Bending of rocks by (*a*) relative movements along cracks and bedding and other parting planes, in the case of the stronger and more rigid rocks ; and (*b*) flowage in the case of the weaker and more plastic rocks		
Flowage . . .		Slaty cleavage (p. 60) Foliation (p. 63)	
			Modes of Occurrence
Flowage and Flow		← Batholiths and Stocks →	
Flow (through fractures, etc.)			Dykes, sills, laccoliths, etc.
(at and near the surface)			Lava flows and volcanic plugs *
Fracture (by explosion) . .			Explosion pipes, pyroclastic accumulations

* These and other volcanic products and structures are dealt with in Chapter XX.

Similarly, when rocks become molten, the material can flow, though it rarely flows freely until the surface is reached. Then extrusion takes place, either quietly (relatively speaking) as lava flows, or explosively, with production of *pyroclastic* (" fire-broken ") rocks. When the pressure of a magma in depth is sufficient to overcome the strength of the rocks or their overhead weight, the magma is impelled to move in the direction of least resistance, either bodily or through fissures and other parting planes, thus forming intrusions of various kinds, some of which extend to the surface. The form and size of an igneous mass as a whole, and its relations to the adjacent rocks (often referred to as the " country rocks ") are called its *mode of occurrence.*

FOLDS

Stratification is a primary structure of sedimentary rocks, due to the deposition of layer after layer of differing or alternating types of sediment. Most sediments were originally

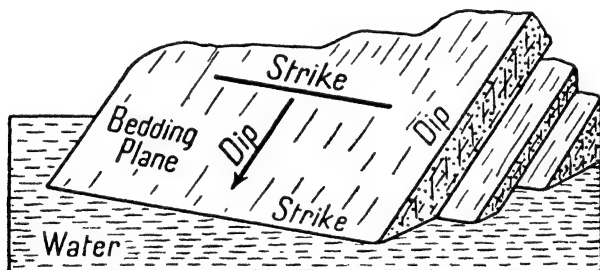



FIG. 23
To illustrate the meaning of the terms *Dip* and *Strike*

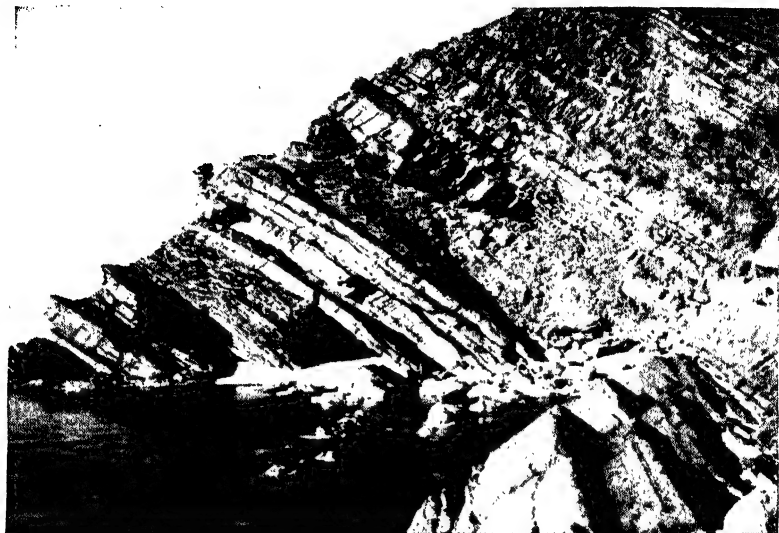
deposited on flat, very slightly inclined surfaces. But in many regions we find that great thicknesses of strata have been tilted, so that they now lie in inclined positions, sometimes for many miles. The tilted beds generally represent one side of a very broad fold. The attitude, or position in the ground of any inclined bed, is accurately described by what is called its *dip* (Fig. 23). The dip is both the direction of the maximum slope

[*H.M. Geol. Survey*

FIG. 24

Sea cliff of Torridon sandstone, showing dip and strike, Cailleach Head, Ross-shire

down a bedding plane and the angle between the maximum slope and the horizontal. The direction is measured by its true bearing, as so many degrees east or west of north, the compass reading being suitably corrected for magnetic variation. The angle is measured with a clinometer. The *strike* of an inclined bed is the direction of any horizontal line along a bedding plane ; the direction, for example, of the intersection of the bed with still water or level ground. It is at right angles to the dip direction (Fig. 24).

When beds are upfolded into an arch-like form (with the lower beds within the upper) the structure is called an *anticline*, because the beds then " incline away " from the crest on either side (Plate 12A). When the beds are down-folded into a trough-like form (with the lower beds outside the upper) the structure is called a *syncline*, because in this case the beds on either side " incline together " towards the keel (Plate 12B). The two sides of a fold are described as its *limbs*, the limb which

Dorien Leigh, Ltd.

(A) Well-developed jointing in sandstone, Eaglehawk Neck, Tasmania

E.N.A.

(B) Columnar jointing in basalt, The Giant's Causeway, Co. Antrim

PLATE 15

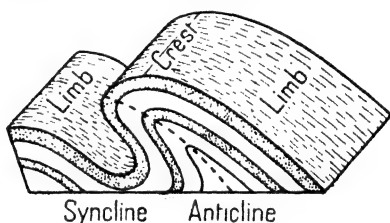
(A) Jointing in granite, castellated cliffs of Land's End, Cornwall

(B) Normal fault in beds of sandstone and shale (Coal Measures), Mossend, Lanarkshire

is shared between an anticline and its companion syncline being called the middle limb. The plane which bisects the angle between the limbs is the *axial plane*, and the *axis* of the fold along any particular bed (about which the bed is folded) is the line of intersection of the axial plane with the surface of that bed. If the axial plane is vertical, the fold is upright and symmetrical, and the crest coincides with the axis. If the axial plane is inclined, the fold is also inclined ; relative to the vertical it is, of course, unsymmetrical (Fig. 25).

As they are traced along their axes, folds sooner or later die out ; and here, or wherever the axes are not horizontal, they are said to pitch, *pitch* being simply the dip of the beds along the axis of a pitching fold. Anticlines and synclines are thus like more or less elongated canoes, upside down or

Fig. 25

Inclined folds, with the upper strata removed to show the surface of one particular bed. The trace of an axial plane is marked by the dotted line

right way up. *Domes* and *basins* represent the limiting cases in which the beds dip in all directions, outwards from, or inwards towards, the centre of the structure. Between these and folds that extend for many miles there is every gradation. Such structures must not, of course, be confused with hills and valleys, for they refer solely to the attitudes of the bedrocks below the surface, and not to the relief of the surface itself.

Folds range in intensity from broad and gentle undulations to steep-sided, highly compressed folds in which the beds may be turned on end, and the limbs of anticlines (or, in other words, the upper limbs of synclines) turned over even beyond the vertical (Plates 13 and 81). In the Southern Uplands of Scotland the rocks have been so intensely compressed that the limbs of the closely packed folds have become practically parallel. Folding of this " concertina " type is described as *isoclinal* (Plate 69A). In this region, and also in the Lake

District, the puckers and smaller folds are superimposed on broad anticlinal and synclinal folds of a much larger order. An anticlinal complex of folds of different orders is called an

FIG. 26
Schematic section across an anticlinorium and a synclinorium

anticlinorium, and the complementary synclinal complex a *synclinorium* (Fig. 26).

When a pack of cards is bent into a fold, slipping between the adjacent cards invariably occurs. Similarly, during the growth of anticlines, the outer beds shear or creep along the inner ones towards the axial plane, while in synclines the lower beds move in the same way under the higher ones. Plastic

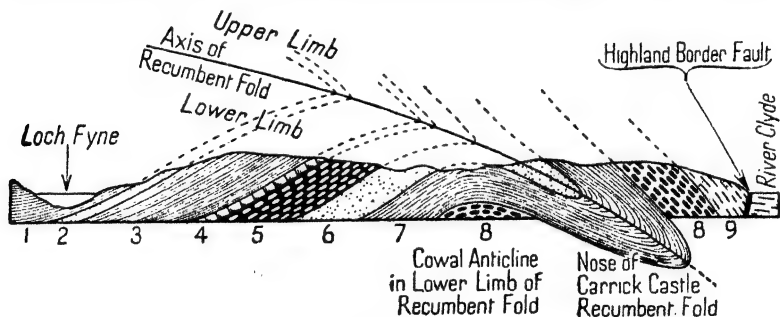



FIG. 27
Section across the Carrick Castle recumbent anticline (Argyllshire). The strata of the lower limb are upside down (1 to 9 = oldest to youngest), and have themselves been folded into an anticline (the Cowal anticline)

or " incompetent " beds, like shale, tend to creep by flowage more readily than stronger or " competent " beds, and for this reason they become squeezed out and thinned in the limbs and

thickened towards the axes. It is during this flowage that shales tend to become slaty, the resulting cleavage planes being parallel to the axial planes. Thus, in an anticlinorium the cleavages are disposed across the whole structure like the ribs of a fan.

An overturned fold, or *overfold*, has one of its limbs inverted, and if the latter approaches a horizontal attitude the overfold is described as *recumbent* ; the beds of the middle limb (the lower limb of the anticline and the upper limb of the underlying syncline) are then upside down. Parts of the Grampians are carved out of a gigantic recumbent fold (Fig. 27). In

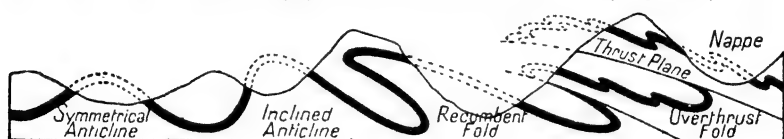



FIG. 28

Diagrammatic section showing various types of folding and thrusting

structures of this kind part of the middle limb may be sheared or squeezed out altogether. Further development of the structure then results in the rocks of the upper limb being pushed bodily forward along the plane of shearing. The latter has become a *thrust plane* and the structure an *overthrust fold* (Fig. 28).

JOINTS

The stronger beds in a folded series of strata become ruptured when they are bent, the cracks being known as joints. Unfolded rocks are also commonly divided into blocks by jointing. If we examine a quarry or cliff section of sandstone or limestone, we find that in addition to the bedding planes the rock is traversed by fractures that are generally approximately at right angles to the stratification, and therefore nearly vertical when the beds are flat (Plates 8A and 14A). Joints frequently occur in sets consisting of two series of parallel joints, one series, if the beds are inclined, approaching in trend to the dip direction and the other to the strike. Such

joints are of great assistance to the quarryman in his task of extracting roughly rectangular blocks of stone, especially the "master joints," which are often remarkably persistent and strongly developed. In most rocks, however, there are subordinate joints which cut across the main sets, thereby dividing the rocks into irregular angular blocks.

Joints may be due either to shearing under compression or to tearing apart under tension. Shear joints tend to be clean cut and tightly closed (in unweathered rocks), whereas tension joints are more irregular, rough, and open. At the surface, joints of all kinds are very susceptible to the attack of weathering agents ; they are readily opened up by the work of rain, frost, wind, and plant roots. It is due to this opening of joints and bedding planes that cliffs and mountain scarps often resemble roughly hewn masonry (Plates 15A and 32A). Along the shore waves attack the rocks selectively along joints and the influence of the joint pattern is often clearly shown in the outlines of inlets, caves, and skerries (Plate 67A). The joint pattern may also control the course of rivers, the joint planes themselves commonly forming the walls of steep-sided gorges and canyons (Plate 1).

In igneous rocks tensile stresses are set up by contraction during cooling. In granite masses three series of joints are commonly developed, two being nearly vertical and the third approximately parallel to the surface. The latter produces a *sheet* structure, which becomes conspicuous when the rock is exposed to weathering. The tors on granite moorlands are divided up into gigantic blocks with a bold architecture like that of a cyclopean fortress (Fig. 62).

A quite different architectural effect is produced by the columnar jointing of certain basalts and other fine-grained and compact igneous rocks (Plate 14B). Somewhat similar sets of polygonal cracks can be seen in the dried-up mud of a marsh or river flat that has been exposed to the sun (*cf.* Plate 19). Mud cracks result from shrinkage due to loss of water from the surface layer. The polygonal cracks of basaltic sheets are due to contraction during cooling. When a hot homogeneous rock cools uniformly across a plane surface, the

contraction is equally developed in all directions throughout the surface. This condition is mechanically the same as if the contraction acted towards each of a series of equally spaced centres. Such centres (*e.g.* C, 1, 2, 3, etc. in Fig. 29a) form the corners of equilateral triangles, and theoretically this is the only possible arrangement. At the moment of rupture the distance between any given centre C and those nearest to it (*e.g.* 1–6) is such that the contraction along lines such as C—1 is just sufficient to overcome the tensile strength of the rock. A tension crack then forms half-way between C and 1 and at right angles to the line C—1. As each centre is surrounded by

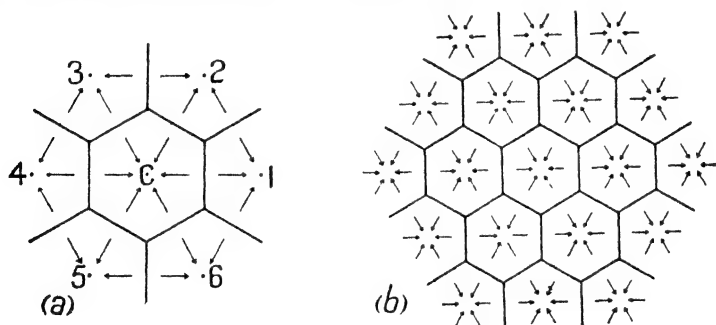



FIG. 29

To illustrate the formation of an ideal hexagonal pattern of joints by uniform contraction in a plane towards evenly spaced centres

six others (1 to 6 in Fig. 29a), the resultant system of cracks is hexagonal. Once a crack occurs somewhere in the cooling layer the centres are definitely localized, and a repeated pattern of hexagonal cracks spreads almost simultaneously throughout the layer (Fig. 29b). As cooling proceeds into the sheet of rock the cracks grow inwards at right angles to the cooling surface, and so divide the sheet into a system of hexagonal columns.

Neither the physical conditions nor the rocks are usually sufficiently uniform to ensure perfect symmetry, and the actual result is a set of columns with from three to eight sides, six, however, being by far the commonest number. Vertical contraction is relieved by cross joints, which are generally

either concave or convex, and the columns are thus divided into short lengths. The resulting appearance of well-trimmed masonry is often remarkably impressive, as in the tessellated pavement of the Giant's Causeway, and the amazing architecture of Fingal's Cave in Staffa (Plates 3 and 14B). Comparable, but usually cruder and less regular columnar jointing develops during the cooling of sills and dykes. In a dyke the cooling surfaces are the vertical walls, and the resulting columns are therefore horizontal.

FAULTS

A fault is a fracture surface against which the rocks have been relatively displaced. Vertical displacements up to thousands of feet and horizontal movements up to many miles are well known, but in no case is there any reason to suppose that the total displacement occurred in a single catastrophic operation. Earthquakes commonly result from sudden movements along faults that are still active, but the fault movements are rarely more than a few feet at a time. The various types of faults depend on the relationships between the three principal stresses referred to on page 69, assuming, of course, that in the circumstances of each case the stress difference is sufficient to bring about fracture and movement. The vertical stress may be due to gravity or magmatic pressure, and the horizontal stresses to lateral earth compression or tension. Three types of faults occur most commonly, but the details given below by no means exhaust the possibilities, which may be tantalisingly complex.

In connection with the inclination of fault planes, it should be kept in mind that shear planes curve towards the locus of least resistance. This is well shown by landslides (Fig. 63). When the Panama Canal was dug, the materials supporting the hillsides were locally removed, and there was much downward slipping along concave surfaces that began steeply on the heights and curved round to the horizontal at the level of the canal floor. On the other hand, the direction of least resistance may be far below the surface, just where it might

be thought that the obstruction would be irresistible. This possibility arises when there are down-dragging movements in progress in the depths.

The sides of a clean-cut fault plane may be polished or striated by friction between the moving blocks ; such surfaces are known as *slickensides.* Sometimes, instead of a single fracture, there are two or more, forming a strip consisting of a sheet of crushed rock of variable thickness. This is distinguished as a *fault zone,* and the shattered material within is called a *fault breccia.*

(*a*) *Normal Faults* (Figs. 30 and 31 and Plate 15B).—The vertical stress is the greatest of the three. The resulting fracture is generally inclined at an angle between 45° and the vertical.

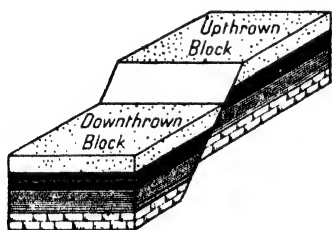



Fig. 30
The relative movement involved in a normal fault. Part of the fault plane is left unshaded

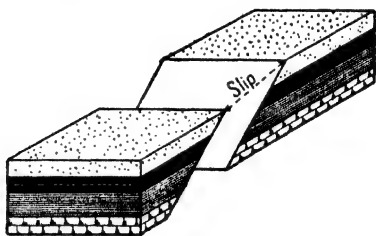



Fig. 31
Oblique-slip normal fault, illustrating the meaning of the term *slip*

The beds abutting against the fault on its upper face or " hanging wall " are displaced downwards relative to those against the lower face or " footwall." The terms "downthrow" and " upthrow " for the two sides are, of course, purely relative. In faults recently active the footwall is exposed at the surface as a fault scarp, and survey measurements sometimes show that both sides were uplifted ; one, however, being heaved up more than the other. More usually, the two sides have moved in opposite directions. Normal faults involve an extension of the faulted beds. A boring through the fault would fail to penetrate some particular bed altogether, passing between its ruptured ends. Such extension indicates that freedom of

movement was possible towards the direction of least resistance; the minimum stress in many cases appears to have been a tension, involving stretching instead of compression.

(*b*) *Reverse or Thrust Faults* (Fig. 32).—The vertical stress is the least of the three. When the resulting fracture is inclined at an angle between 45° and the horizontal, as it often is, the corresponding fault is described as an *overthrust*. High-angle thrusts or reverse faults are, however, far from rare. But whatever the angle, the beds on the upper side are thrust up the fault plane relative to those below. Shortening of the faulted area is thus involved, and the operation of powerful tangential compression is obviously indicated. In overthrusts the upper block may be driven forward for many miles (Fig. 33). As already pointed out (page 75) overthrusts commonly develop along the middle limbs of recumbent folds. In the Alps and

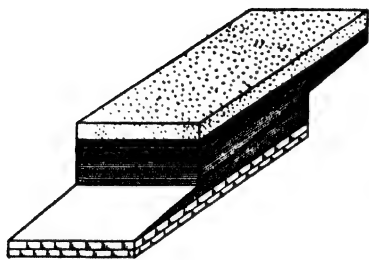



FIG. 32
Reverse or thrust fault

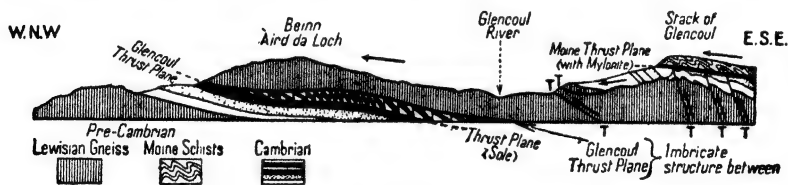



FIG. 33
Section across the North-West Highlands of Scotland to illustrate overthrusting and imbricate structure. For Moine Thrust see Fig. 180

other great mountain ranges enormous overthrust folds and overthrust blocks have been propelled far from their original "roots." Such far-travelled rock-sheets are called *nappes*. Along the thrust plane (Plate 16) of a great overthrust or nappe the crushing is generally very severe, and a hard, streaky, or banded rock, to which the name *mylonite* is given, may ultimately be produced from the pulverised and rolled-out materials (Fig. 34).

[H.M. Geol. Survey

Thrust plane in Cambrian limestone, exposed by river erosion, Traligill River, Inchnadamff, Sutherland

[R. Welch

(A) Dolerite dyke cutting Chalk and Tertiary basalt lavas, Cave Hill, Belfast

[H.M. Geol. Survey

(B) Dyke cutting breccia, Kiloran Bay, Colonsay

[*J. J. H. Teall*

FIG. 34

Photomicrograph of mylonite formed from Lewisian gneiss along a thrust plane near Laxford, North-West Highlands

(*c*) *Tear Faults* (Fig. 35).—The vertical stress is intermediate between the maximum and minimum horizontal stresses. The resulting movement is predominantly horizontal, the fracture being vertical or nearly so. Tear faults are commonly developed in nappes, where they naturally arise if one part of a nappe has been driven forward further than the

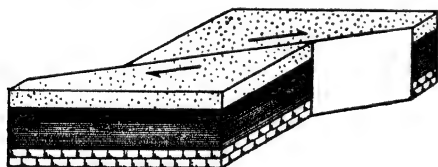



FIG. 35

Tear fault ; also known by the terms *transcurrent* or *strike-slip* fault

adjoining parts. Other tear faults appear to be due to rotational movements (about a vertical axis) of certain crustal blocks relative to their surroundings. Each individual movement is a small jerk, like that of the hands of a clock placed horizontally. A sudden jerk of this kind along a tear fault

hundreds of miles long caused the earthquake that wrecked San Francisco in 1906. Roads, fences, and water mains that crossed the fault were cut through and the ends displaced by several feet. During its history a cumulative movement of many miles has taken place along this fault. On the Pacific side the apparent movement is towards the north, as if the Pacific floor were moving in an anticlockwise direction against the North American continental block (*cf.* Fig. 184).

Modes of Occurrence of Igneous Intrusions

The forms and attitudes of igneous rocks which have been injected into crustal rocks largely depend on their relation to the parting planes of the invaded formations. This is seen

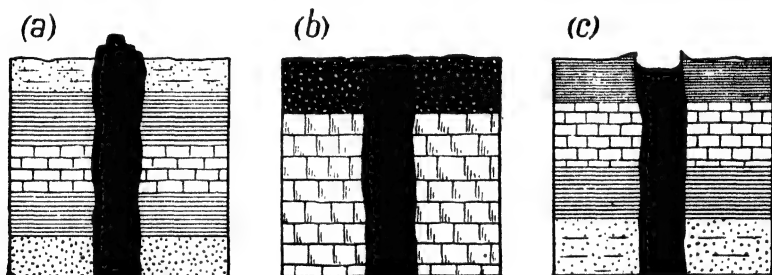



Fig. 36

Diagrams to illustrate dykes and their surface features:
(*a*) Dyke more resistant to erosion than wall rocks
(*b*) Dyke and wall rocks equally resistant (*cf.* Plate 17A)
(*c*) Dyke less resistant than wall rocks

most clearly where the strata have remained horizontal or have been only gently tilted or folded. One of the commonest signs of former igneous activity is provided by the wall-like intrusions called *dykes* (Fig. 36 and Plate 17). Here the magma has ascended through approximately vertical fissures, forcing the walls apart as it rose, and so, on cooling, becoming a vertical sheet of rock with roughly parallel sides cutting across the bedding planes. Such intrusions are said to be ***transgressive*** or ***discordant***. In certain circumstances the magma may open

up a passageway along a bedding plane, making room for itself by uplifting the overlying rocks. The resulting tabular sheet of rock (Fig. 37) is called a *sill* (Anglo-Saxon, *syl*, a ledge). Intrusions that are parallel to the adjacent stratification are said to be *concordant*.

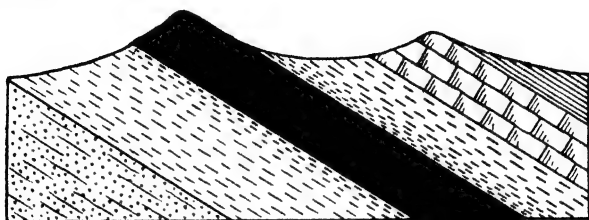



FIG. 37
Ideal section through a sill (black) in inclined strata

Dykes vary greatly in thickness, from a few inches to hundreds of feet, but widths of five to twenty feet are most common. There is also great variation in length, as seen at the surface, from a few yards to many miles. Dykes are very numerous in some regions of igneous activity. Along a fifteen-mile stretch of the coast of Arran, for example, a swarm of 525 dykes can be seen, the total thickness of the dykes being 5,410 feet. Here the local extension of the crust has been more than one mile in fifteen. Farther north, focused on Mull, there is another great swarm of dykes, some of which can be traced at intervals across southern Scotland into the north of England (Fig. 38). Most of these dykes are dolerites of various kinds, though along the margins the rock is generally of finer grain, owing to chilling by the walls, and may be basalt or even tachylyte. The wall rocks themselves show the effects of thermal metamorphism. Coal seams in contact with dykes are reduced to a hard mass of natural coke. When a dyke is more resistant to weathering and erosion than its walls, it projects as a prominent ridge, sometimes running across the country like a wall. On the other hand, if the walls are more resistant, the dyke is worn away (*e.g.* by sea waves) into a long narrow trench or cleft. In its ordinary usage, the word " dyke " may refer to either a ditch or a wall (*cf.* Fig. 36).

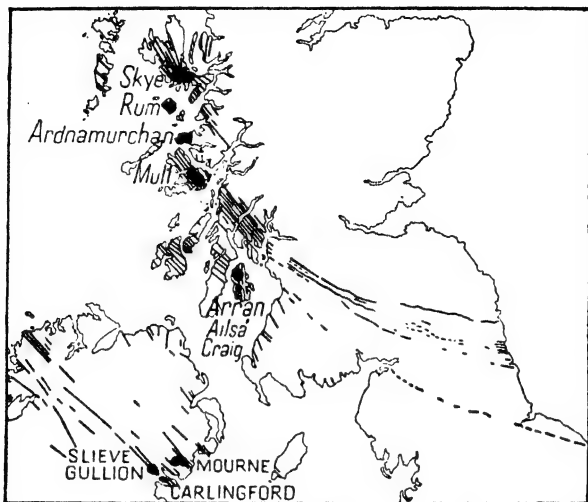



Fig. 38

Map showing the Tertiary dyke swarms in the British Isles, and their relation to the Tertiary plutonic centres. For a view of the major intrusions of Skye see Plate 18B

The classic example of a *sill* is the Great Whin Sill of the north of England (Figs. 39 and 40). *Whin* or *whinstone* is a quarryman's term for any dark-coloured rock, such as basalt or dolerite, which can be used as road-metal. Beginning in

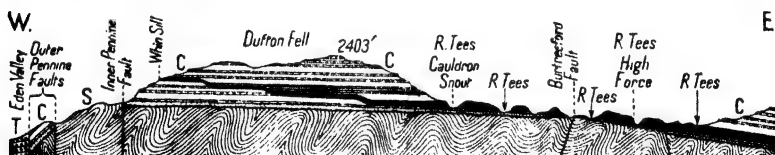



Fig. 39

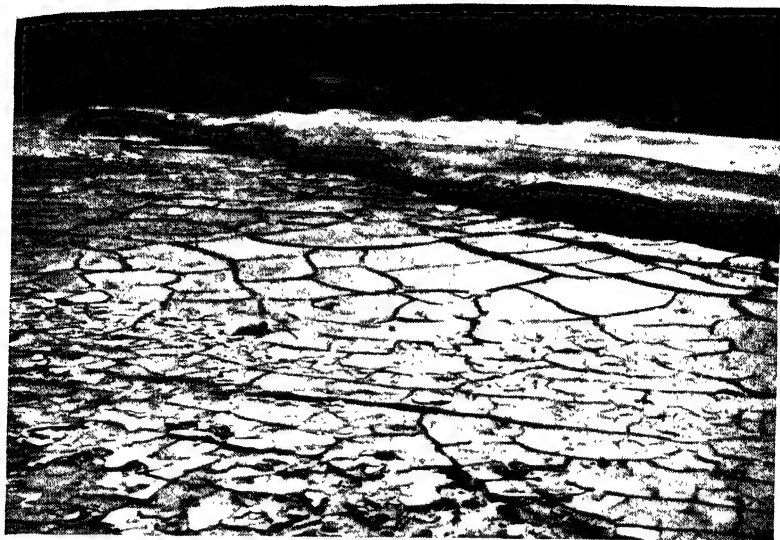
Section across the Northern Pennines to show the Great Whin Sill and its thinning and upstepping towards the west. Length of section equals 17 miles. T = Triassic. C = Carboniferous. S = Silurian and Ordovician

the north of Northumberland, the surface outcrop of the edge of the Whin Sill swings round to the castled crags of Bamburgh and seawards to the Farne Islands. Appearing again on the coast below the ruins of Dunstanburgh Castle, it can be followed across Northumberland towards the River North Tyne.

[F.N.A.

(A) The Great Whin Sill and the Roman Wall, Cuddy's Crag, Northumberland

[G. P. Abraham, Ltd., Keswick

(B) Tertiary plutonic intrusions, Skye. Red Hills (granite), with Cuillin Hills (gabbro) in the left background

[H.M. Geol. Survey

(A) Mudcracks, Torside Reservoir, Longdendale, Cheshire

[H.M. Geol. Survey

(B) Filled-in mudcracks in mudstone of Old Red Sandstone age, Clairdon shore, east of Thurso, Caithness

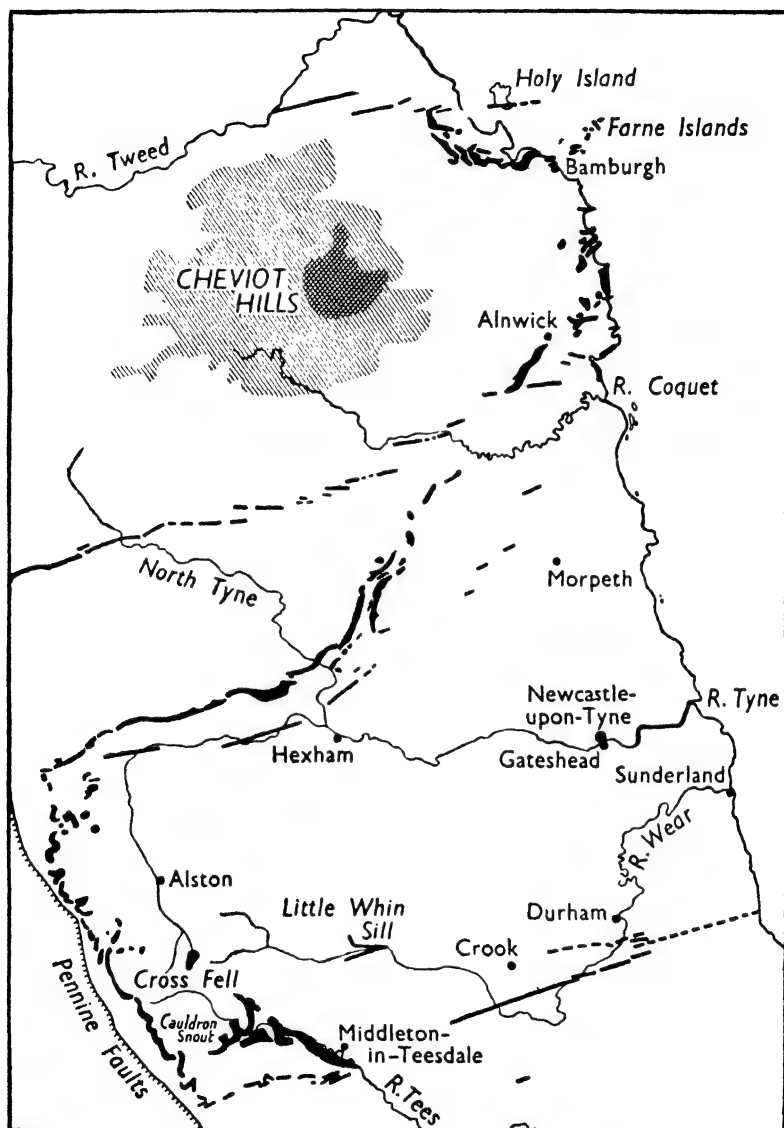



Fig. 40
Map of the Great Whin Sill and related dykes

Then for miles its tilted and weather-worn scarp boldly faces the north (Plate 18A), and here, with an eye for the best defensive line, the Romans carried their famous Wall along its crest. To the south-west it outcrops in the valleys that notch the western margin of the Pennines. Inland from the exposed edge, the Upper Tees cuts through it in the waterfalls of Cauldron Snout and High Force. Near Durham it is encountered in depth, over a thousand feet below the surface. The thickness of the sill varies from a few feet, through a general average of nearly 100 feet, to more than 200 feet. In places it divides into two or more sills at different levels, and locally it betrays its intrusive character by breaking obliquely across the strata from one set of beds to another. This observa-

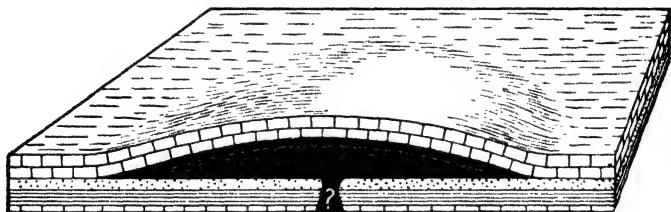



FIG. 41
Diagram to illustrate the form of an ideal laccolith

tion proves that the Whin Sill is not a lava flow, and further evidence of this is provided by the fact that the rocks above it are metamorphosed, as well as those below (Figs. 18 and 39).

Instead of spreading widely as a relatively thin sheet, an injected magma, especially if it is very viscous, may find it easier to arch up the overlying strata into a dome-like shape (Fig. 41). Such intrusive forms are typically developed to the east of the Rockies, where they were first described by Gilbert, who called them *laccoliths* (Gr. *laccos*, a cistern, *lithos*, a rock). There are few good examples of laccoliths in Britain, though many stocks have been wrongly called laccoliths. Stocks are discordant intrusions, whereas laccoliths, like sills, are concordant.

Intrusions, which on the whole are concordant and have a saucer-like form, are distinguished as *lopoliths* (Gr. *lopas*, a

shallow basin). The best-known examples are of extraordinary dimensions, the largest, that of the Bushveld in South Africa (Fig. 42), being nearly as extensive in area as Scotland. The sagging of these great sheets would seem to be an inevitable consequence of the transfer of enormous masses of magma from the depths to the upper levels of the crust.

When magmatic pressure is exerted upwards from a more or less circular area in depth (like the top of a dome), the resulting cracks in the overlying rocks may be either radial or concentric, according to circumstances. Dykes arranged radially occur around certain volcanic centres from which the outer cover of lavas and pyroclasts has been stripped by denudation. Ring-shaped intrusions are less common, but

FIG. 42

Diagrammatic section across the lopolith of the Bushveld, Transvaal. Length of section about 315 miles

1. Crystalline rocks of the Basement Complex 2. Transvaal system 3. Rooiberg series 4. Sills of dolerite 5. Norite (a variety of gabbro) 6. Granite 7. Pilandsberg volcanic centre

are characteristically developed around the intrusive centres of the west of Scotland and the north of Ireland (shown in Fig. 38). In the type thought to be due to magmatic pressure the fractures have the form of an inverted cone. Uplift of an inner cone relative to an outer one involves opening of the crack between them into a fissure. Injections of magma then give a series of concentric shells, dipping inwards, as illustrated in Fig. 43. *Cone-sheets*, as these intrusions are called, are remarkably well displayed in Mull, Ardnamurchan, and Skye.

If, on the other hand, the upper rocks are left relatively unsupported, they tend to break along concentric fractures like those shown in Fig. 44. Subsidence then opens the way for injection of magma. The resulting intrusions are called *ring-dykes*; they differ from cone-sheets in being nearly vertical,

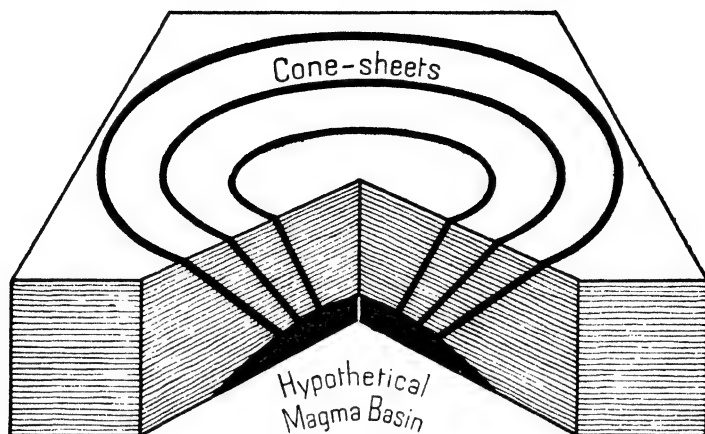



FIG. 43
Block diagram to illustrate the form of an ideal series of cone-sheets, and their probable relationship to an underlying magma basin

dipping outwards at steep angles, and also in being much thicker. Now these two characteristics are obviously mutually inconsistent, since sinking of a cylinder or steep-sided cone could not possibly make room for the very thick ring-dykes

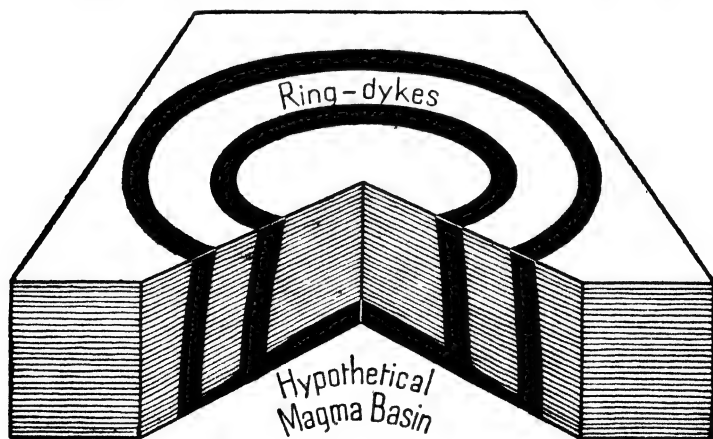



FIG. 44
Block diagram to illustrate the form of an ideal series of ring-dykes and their supposed relationship to an underlying magma basin

that are actually known. The ring-dykes must, therefore, have been emplaced by either *displacing* or *replacing* the wall-rocks of a ring-fracture, or the rocks lying between two or more concentric ring-fractures. How this difficulty can be met we shall consider in connection with batholiths, where the "space problem" has to be squarely faced.

Batholiths (Gr. *bathos*, depth) are gigantic masses of essentially igneous rocks, generally composed of granite or granodiorite, with highly irregular dome-like roofs, and walls that plunge downwards so that the intrusions enlarge in depth and

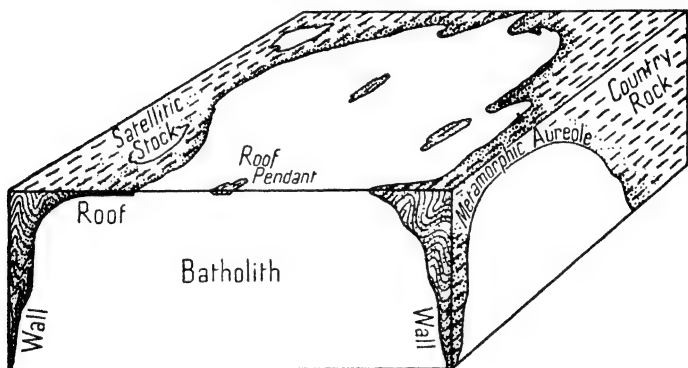



FIG. 45
Block diagram to illustrate the characteristic features of a batholith

appear to be without visible foundations (Fig. 45). They occur in the hearts of mountain systems of all geological ages and are seen wherever denudation has cut down sufficiently deeply. Although in detail their margins are markedly discordant towards the surrounding rocks, they are generally elongated parallel to the general trend of the mountain systems in which they are found. Some of the batholiths of western America have been exposed over lengths of many hundreds of miles, the width being usually about a tenth of the length or less.

Smaller intrusions of similar type, but less elongated and with areal dimensions of only a few square miles or less, are called *stocks*. Many of these are probably offshoots from under-

lying batholiths, of which only the highest parts have been exposed to view by denudation. Mining operations have often shown this to be the case. When a stock has a roughly circular outline, like the Shap granite of Westmorland, it is sometimes referred to as a *boss*.

Some examples of stocks and bosses may have come into position by a process called *cauldron subsidence.* Part of the cylindrical block of country rock enclosed within a vertical ring-dyke may founder into the underlying magma reservoir, while volcanoes are active at the surface. The space between the lava roof and the sunken block fills with magma which consolidates as, say, granite. On denudation the boss of granite is revealed by the removal of the volcanic rocks. In Glencoe there is visible evidence on the hillsides that such subsidences have actually occurred. In recent times a similar process, involving the collapse of the roof itself (*i.e.* of part of a volcanic cone), has been responsible for the formation of giant volcanic calderas (*cf.* Fig. 240).

The Emplacement of Batholiths

Cauldron-subsidence cannot be the mechanism by which batholiths have been emplaced, because many of them still retain patches of their original roof of country rocks. Moreover, the mechanism implies the presence in depth of a magma reservoir of batholithic dimensions which itself calls for explanation. As in the case of thick ring-dykes, the question has to be faced : What has happened to the crustal rocks that formerly occupied the space now taken up by the batholith ? If the batholith was entirely formed by the consolidation of magma that ascended bodily from below, then the pre-existing rocks must have been displaced upwards, sideways, or downwards. But only a part of the space required can be made available in ways like these. Observations of roof and wall show that outward displacements of the country rocks do occur, but only on a relatively small scale, such as would be inevitable around any large expanding mass.

Downward displacement seems at first sight to be more

promising. This involves shattering of the roof rocks by thermal expansion, dislodgment of the fragments by the penetration of gases and tongues of magma into cracks, and finally the engulfment and sinking of the blocks. This process is called *magmatic stoping.* Inclusions of country rocks of all sizes, more or less intensely metamorphosed, are often preserved in the upper levels of stocks and batholiths. They are known as *xenoliths* (Gr. *xenos*, foreign). In depth, however, they become gradually smaller and less numerous, and more and more like the granitic rocks enclosing them, until finally they disappear altogether. Evidently they have been incorporated into the granite and the space problem remains. Moreover, long " islands " of country rocks like those of the metamorphic aureole can sometimes be recognized in the granite, their structures remaining in continuity with those of the bordering country rocks, though they may often be no more than vague shadowy outlines, seen through a veil of granitization (Plate 11B). Black metamorphosed dolerite dykes, older than the batholith, can sometimes be traced into it as partly granitized " ghosts." Since the heavy dyke rocks did not sink, there is no reason to suppose that the associated metamorphosed sediments could have done so.

The stoping hypothesis has to face another serious difficulty. If granite magma ascends in great bulk towards the surface in this way, it should often have broken clean through the crust to form gigantic volcanoes erupting rhyolite and obsidian and the corresponding pyroclasts. But this has very rarely happened, as the retention of the original roof clearly proves. Moreover, if granite magma rose from the depths in quantities corresponding to the enormous volumes of batholiths, it would be by far the most abundant of all magmas. In this case rhyolite should be the most abundant of all volcanic rocks. But it is not. Although granite and granodiorite are easily the commonest of plutonic rocks, it is basalt that is the commonest of the volcanic rocks. This striking fact strongly suggests that the volume of actual magma concerned in the development of batholiths was relatively small in comparison with their enormous bulk.

Since we cannot solve the space problem by sinking the pre-existing rocks out of the way or by pushing them upwards or sideways, it follows that a high proportion of the material of the original rocks must still be there, though now transformed into granite and associated types of igneous rocks. Every positive line of evidence supports this view, including that already summarized on p. 65. Apparently the original rocks were not invaded by granite magma as such, but by hot granitizing fluids rich in gases. These soaked through the rocks, changing their composition, metamorphosing them with an intensity that reached ultrametamorphism, thereby leading to the generation of granitic magma *in situ*, and rendering the whole mass mobile, so that it became igneous.

SUGGESTIONS FOR FURTHER READING

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Chapter VII

ROCKS AS THE PAGES OF EARTH HISTORY

The Key to the Past

So far we have dealt with rocks as materials which have been formed from pre-existing materials by the action of geological processes. Rocks are also the pages of the book of earth history, and the chief object of historical geology is to learn to decipher these pages, and to place them in their proper historical order. The fundamental principle involved in reading their meanings was first enunciated by Hutton in 1785, when he declared that " the present is the key to the past." Rocks and characteristic associations of rocks, with easily recognizable peculiarities of composition and structure, are observed to result from processes acting at the present day in particular kinds of geographical and climatic environments. If similar rocks belonging to a former geological age are found to have the same peculiarities and associations, it is inferred that they were then formed by the operation of similar processes in similar environments.

We have already, as a matter of ordinary common sense, had occasion to apply this principle. The presence in a limestone of fossil corals or ammonites, or of the shells of other marine organisms, indicates that the limestone was deposited on the sea floor, and that what now is land once lay beneath the waves. The limestone may pass downwards or laterally into shale, sandstone, and conglomerate. The last of these represents an old storm beach, and it indicates the shore line where land and sea came together. Elsewhere, old lava flows represent the eruptions of ancient volcanoes ; beds of rock salt point to the former existence of inland seas that evaporated in the sunshine ; seams of coal, which are the compressed remains of accumulations of peat, suggest widespread swamps and luxuriant vegetation ; and smoothed and striated rock surfaces associated with beds of boulder clay prove the former ex-

tension of glacial conditions. In every case the characters of older formations are matched with those of rocks now in the making.

Even the weather may be recorded in the structures of the rocks. A brief rain shower falling on a smooth surface of fine-grained sediment leaves its marks as little crater-like pittings known as *rain prints.* Sun cracks develop in the mud flats of tidal reaches or flood plains when the mud dries up and shrinks (Plate 19A). Occasionally it happens that the polygonal cracks become filled with wind-blown sand before the next tide or flood sweeps over the area. Then, instead of being obliterated, they have a chance to become permanent. Thus it comes about that similar structures are preserved in older beds of corresponding origin (Plate 19B). As far back as geological methods can be applied to the earth's history, such relics of " fossil weather " prove that wind, rain, and sunshine have always been much the same as they are to-day. Nevertheless, the distribution of climates over the earth's surface has varied in a most astonishing way.

In our own country the work of former ice sheets and glaciers is still written conspicuously in the landscapes and superficial deposits left behind when the ice began to retreat about 20,000 years ago. In striking contrast, the very much older clay through which the London tubes are bored contains remains of vegetation and shells and reptiles like those of the modern tropics. In still earlier periods there is evidence of desert conditions. Elsewhere the vicissitudes of climate are equally startling. In India and in central and southern Africa there is clear proof that while Britain was a land of swampy, tropical jungles (the time of coal formation) these lands were buried under great ice sheets like those of Greenland and Antarctica at the present day. In Greenland, however, the older rocks contain remains of vegetation that could have grown only in a warm climate, while near the South Pole Captain Scott found beds of coal, pointing to conditions very different from those of to-day.

We may next turn to certain examples of Hutton's principle which can be applied to problems connected with earth move-

ments. When sand is deposited from currents of shallow water, shoals and sandbanks are often built up. The bedding of a growing sandbank follows the gently curved slopes on which the sand is dropped, giving a pattern in cross section which, under ideal conditions, resembles that shown in Fig. 46a. With changing conditions, possibly during a storm, the upper part of the sandbank is swept away, and the bedding planes are sharply truncated by an erosion surface such as AB.

Later on, another group of sandbanks is likely to be deposited on the flat surface thus provided. So, in a quarry or

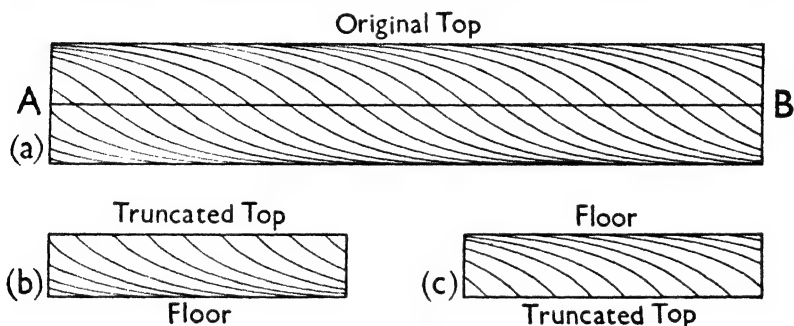



FIG. 46

Sections to illustrate current bedding and its value in determining whether a bed is right way up or upside down

(*a*) The current-bedding structure is complete
(*b*) The upper part has been eroded off down to AB. The truncated current-bedding pattern is the right way up
(*c*) The truncated current-bedding pattern is upside down

cliff exposure of an old sandstone, we may find that within certain bands the bedding is oblique and variously inclined to the general " lie " of the formation as a whole (Plate 20A). This structure, which is original, and not due to tilting or folding, is called *cross bedding* or *current bedding*. Sand dunes, accumulating from wind-blown sands, also exhibit cross bedding, the pattern of which reproduces, wholly or in part, the characteristic outlines of dunes (Fig. 137).

Now we may take a further step. On page 75 it was stated that some of the rocks of Scotland are upside down for many miles, and the reader may well have wondered how such a

thing can be known. Hutton's principle cannot be applied directly, because no-one has ever witnessed rocks being turned upside down by overfolding. Here, however, cross bedding comes to our aid. Fig. 46b shows that when the upper part of a sandbank is removed by erosion the cross bedding that remains is abruptly truncated at the top, whereas at the bottom it curves gently into the main stratification. The truncated top and the original floor of the band of sandstone are clearly distinguishable. At Kinlochleven and other places in Argyllshire observations of cross bedding show that the floor is now *above* the truncated top (as in Fig. 46c). The beds in which this inverted structure appears are therefore known to be upside down.

Ripple marks, like those seen on a beach after the tide has gone down, are often preserved in ancient sandstones. Desert sands are often beautifully rippled by the wind (Plate 5A), but from the nature of the case wind ripples are very rarely preserved. Ripple marks formed by the to-and-fro movements of water have sharp crests and rounded troughs, and consequently the top and bottom of any bed of sandstone in which they occur can easily be recognized. Where such ripples remain in formations that have been disturbed by severe folding, they, too, can be used to determine whether a particular bed is upside down or not (Plate 20B).

There are, of course, certain processes and rocks to which Hutton's principle cannot be applied. It is impossible to observe granite in the making, nor has it been found possible to make granite experimentally. Precisely for these reasons the problems associated with the origin of granite and other plutonic rocks have long remained matters of speculation, and therefore of controversy. In the circumstances of the case the present provides no key to the past, and all we can do is to suggest processes of diffusion, magma formation and crystallization, which are consistent with the structures and relationships of the rocks in question. Since the available evidence is often difficult to interpret, there is often a choice between rival possibilities. Moreover, the earth's internal behaviour is not limited by our present knowledge of physics and chemistry.

We have certainly no right to assume that all the possibilities have yet been discovered. It is therefore not surprising that attempts to reverse Hutton's principle and use the past as the key to the present have so far been only partially successful.

THE SUCCESSION OF STRATA

To place all the scattered pages of earth history in their proper chronological order is by no means an easy task. The stratified rocks have accumulated layer upon layer, and where

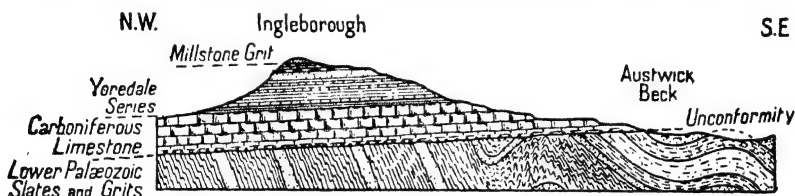



FIG. 47

Section across Ingleborough and its foundations, showing the unconformity between the Carboniferous beds above and the intensely folded Lower Palaeozoic strata below. Length of section equals 4 miles. (*After D. A. Wray*)

a continuous succession of flat-lying beds can be seen, as on the slopes of Ingleborough (Fig. 47), where there has been no inversion of beds by overfolding or repetition of beds by overthrusting, it is obvious that the lowest beds are the oldest, and those at the top of the series the youngest. Where a series of

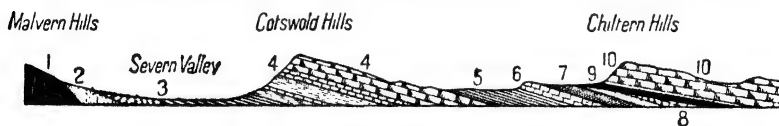



FIG. 48

Section from the Malvern Hills to the Chiltern Hills

1. Pre-Triassic (Pre-Cambrian and Cambrian) 2. Triassic 3. Lias 4. Lower Oolites 5. Oxford Clay 6. Corallian 7. Kimmeridge Clay 8. Portland Beds 9. Gault and Upper Greensand 10. Chalk

beds has been tilted, as between Gloucester and London, the worn-down edges of layer after layer come in turn to the surface and it becomes possible to place a long succession of beds in their proper sequence (Fig. 48).

Around Ingleborough the great limestone platform of the Pennines can be traced over a wide stretch of country, but where the streams have cut through to its base, the limestone is found to lie on the upturned edges of strongly folded and

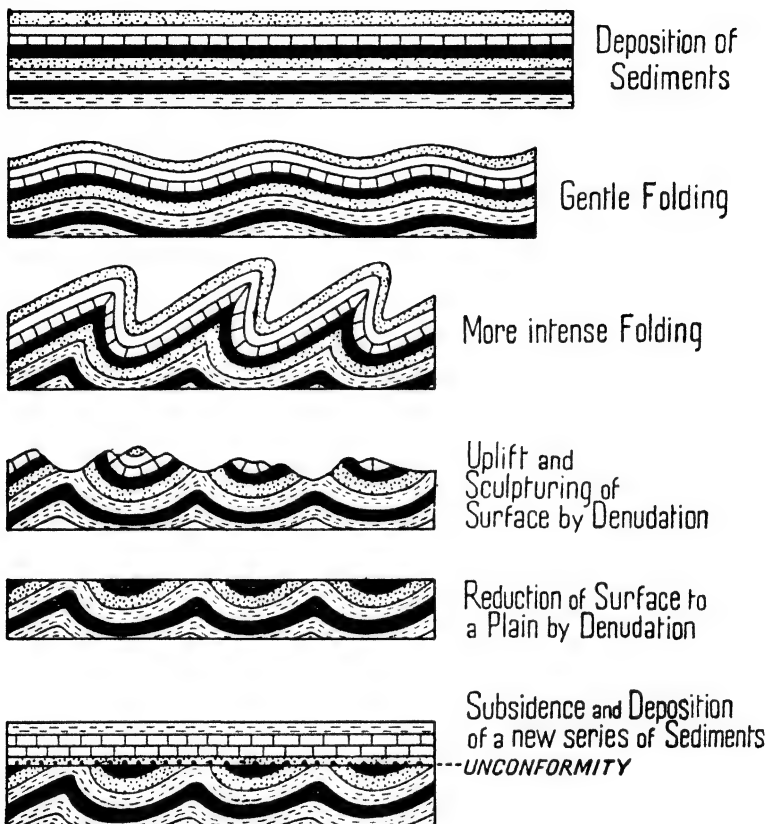



Fig. 49

Diagrams to illustrate successive stages in the development of an unconformity

crudely cleaved beds, as shown in Fig. 47 and Plate 21A. Here there is evidently a sudden break in the continuity of the record. Such a break, which may represent a very long interval of geological time, is called an *unconformity*. The beds above the break in the sequence are said to be conformable,

and to rest unconformably on the rocks below. The latter consist of gritty sandstones and slaty shales. After their deposition on the sea floor as newly formed sediments, they were laterally compressed into folds in the heart of an ancient mountain range—a range which extended throughout Scandinavia and much of the British Isles, and is known to geologists as the Caledonian range because much of Scotland is carved out of its contorted rocks. By denudation the folded grits and slates were gradually uncovered and ultimately reduced to an undulating lowland. Then the worn-down surface was submerged beneath the sea, to become the floor on which the horizontal sheets of the Pennine limestones were deposited. Successive stages of the events which occurred during the time-gap represented by the unconformity are shown by the diagrams of Fig. 49.

In general terms, every unconformity is an erosion surface of one kind or another, representing a lapse of time during which denudation (including erosion by the sea) exceeded deposition at that place. If sediments were deposited there during the interval, they must subsequently have been removed. The time-gap is likely to be represented by strata somewhere else (see Plate 21B), and our next problem is how to recognize such strata if we find them.

The Significance of Fossils

The solution of this problem was the great achievement of William Smith, a land surveyor who was born near Oxford in 1769. As a boy he collected fossils from the richly fossiliferous beds near his home, and in later years he carefully collected suites of fossils from each of the sedimentary formations represented in Fig. 48. He found that while some of the fossils in any particular bed might be the same as some of those from the beds above or below, others were definitely distinctive. Each formation had, in fact, a suite of fossils peculiar to itself. By 1799, when his duties had taken him further afield, he had examined all the formations from the Coal Measures to the Chalk, and everywhere he found the same types of fossils in

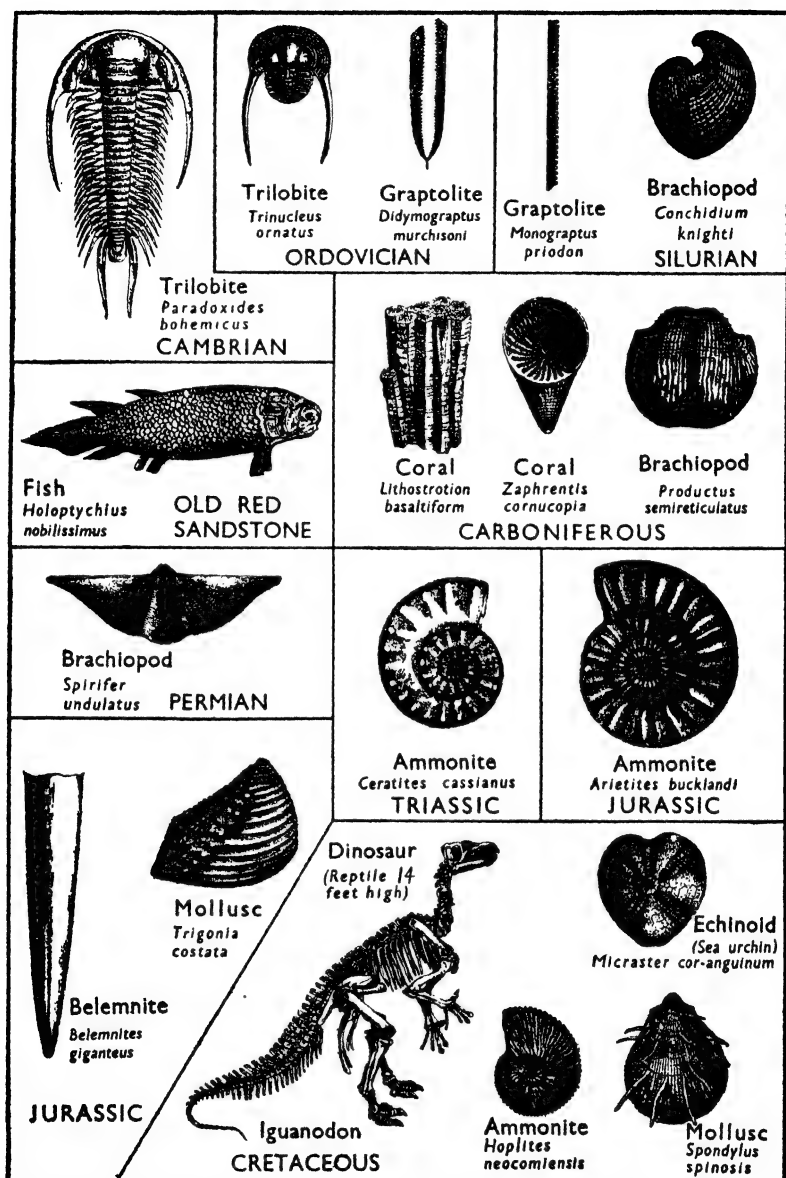



FIG. 50

Some characteristic fossils (Cambrian to Cretaceous)

the same formations and different suites of fossils in different formations. Smith had discovered that the special assemblage of fossils representing the organisms that lived during a certain interval of time never occurred earlier, and never appeared again. The relative age, or position in the time sequence, of a formation could thus be ascertained from its distinctive fossils.

The principle of identifying the ages of strata by their fossils has now been firmly established all over the world. Strata in Europe and Australia, for example, are now known to be practically contemporaneous if they contain similar suites of fossils. The time required for the migration of a particular species from one region to another does not introduce any practical difficulty, because the intervals represented by even the smallest divisions of geological time run into hundreds of thousands or even millions of years, whereas the time required for migration is relatively short. Everywhere the sequence of fossils reveals a gradual unfolding of different forms of life, and thus it becomes possible to divide the whole of the fossiliferous stratified rocks into appropriate divisions, each division having its distinctive fossils and a definite chronological position. Examples of some characteristic fossils are illustrated in Fig. 50.

The Geological Time Scale

As the book of earth history is immensely long, it has been found convenient to classify its contents in much the same way as a long book is divided into volumes, chapters, sections, and paragraphs. Two sets of terms are employed for each division, because it is essential for clarity of thought to discriminate between the strata themselves and the time-intervals they represent :

Divisions of a Book :

Volume	Chapter	Section	Paragraph

Divisions of Strata :

Group	System	Series	Formation

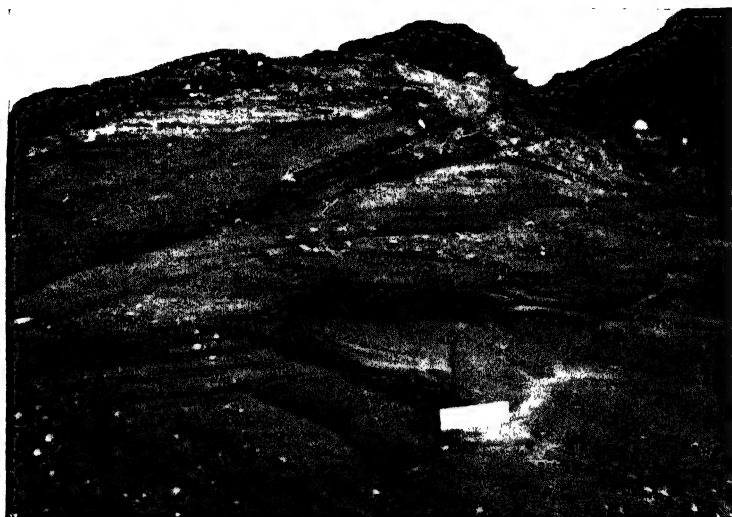
Corresponding Intervals of Time :

Era	Period	Epoch	Age

A coal seam, for example, is a *formation.* A great number of coal seams, together with the associated shales and sandstones, make up the *series* known as the Coal Measures. Below this series comes the Millstone Grit, a series of massive sandstones and grits ; and below this in turn a series characterized by limestone formations. The three series together constitute the Carboniferous *system,* the rocks of which came into existence during the Carboniferous *period.* The latter, with five other periods, make up the Palæozoic *era.*

The table on pages 104 and 105 shows the general scheme of classification by eras and periods which was gradually built up by the pioneer workers of the last century. It will be noticed that the eras have names which broadly express the relations of the life forms then flourishing to those of the present day. Beyond the Palæozoic era there are enormously thick systems of rocks passing down into widespread areas of schists, gneisses, and granites, which form the " basement complex " of any given area. Only rare and obscure remains of life have been found in the less altered sediments of these ancient rocks, of no value for defining world-wide systems. The only collective name for them all is *Pre-Cambrian.*

Igneous Rocks and the Geological Time Scale

To determine the geological ages of igneous rocks it is necessary to observe how they occur in relation to associated stratified rocks of which the ages are known. Volcanic activity of former periods may be represented by volcanic tuffs or lava flows, either of which may be found on old land surfaces or interbedded with sedimentary beds. In the latter case the age of the activity is that of the strata containing the tuffs or lavas. It is less easy to fix the age of an intrusion. The intrusion must, of course, be younger than the youngest of the invaded strata, and it must be older than any beds subsequently deposited on its worn-down surface. A closer upper limit can sometimes be fixed by applying the axiom that a pebble must be older than the conglomerate in which it occurs. Pebbles of Shap granite, for example, easily identified by the flesh-coloured

[H.M. Geol. Survey

(A) Current bedding in Old Red Sandstone, shore at Wemyss Bay, Renfrewshire

[G. W. Tyrrell

(B) Ripple-marked slab of Moine gneiss, folded into a vertical position, with the lower side facing the observer, Glasnacardoch, south of Mallaig, Inverness-shire

[H.M. Geol. Survey

(A) Unconformity: Carboniferous limestone resting on inclined Silurian flagstones, Helwith Bridge, Yorkshire

[H.M. Geol. Survey

(B) Gorge cut in conglomerate of Old Red Sandstone age (deposited during period unrepresented in A). R. North Esk, Angus-Kincardine boundary

porphyritic felspars (*cf.* Fig. 12), occur in the conglomerates at the base of the Carboniferous system in Westmorland. The intrusion is therefore pre-Carboniferous. Since the granite itself invades Ordovician volcanic rocks and Silurian sediments, it must have been emplaced either late in Silurian times or during the Devonian period. The Shap granite is only one of an immense number of intrusions associated with the development of the Caledonian mountain range, to which reference is made below (Fig. 51). In the case of the Whin Sill, the time of intrusion can be fixed as late Carboniferous or early Permian, because it locally cuts Coal Measures, and pebbles of it occur in a Permian conglomerate found in the Vale of Eden not far from the edge of the Pennines.

Although igneous rocks contain no fossils by which they can be relatively dated, they sometimes contain rare radioactive minerals ; and these, in favourable circumstances, have preserved within themselves a record of the actual period which has elapsed since they crystallized. Radioactivity is the process whereby the atoms of certain unstable elements (of which uranium and thorium are the chief) break down into atoms of other elements ; the final stable end-products being the gas helium, and the inert metal lead. Helium, being a gas, tends to escape, but the lead accumulates. Thus a radioactive mineral such as uraninite, which begins its existence as UO_2, has been engaged ever since in keeping a material register of time, after the manner of an hour-glass. Uraninites from comparatively recent igneous rocks contain very little lead, but in those from very old rocks as much as 10 or even 15 per cent. of lead may have accumulated at the expense of the uranium. Since the rate of production of lead from uranium is known, it is possible by making a chemical analysis of a uraninite to determine its absolute age in millions of years. If thorium is also present in the radioactive mineral, as it often is, its output of lead must also be taken into consideration. The expression $Pb/(U+0{\cdot}36Th)$ is called the lead-ratio of the mineral, the symbols representing percentages of the elements concerned ; the corresponding age in millions of years is given approximately by multiplying the lead-ratio by 7,600.

THE GEOLOGICAL

Eras		Periods and Systems	Derivations of Names	
CAINOZOIC	*Kainos* or *Cenos* = recent *Zoe* = life (Recent life)	QUATERNARY*		
		Recent *or* Holocene	*Holos* = complete	'cene' from *Kainos* = recent
		Glacial *or* Pleistocene	*Pleiston* = most	
		TERTIARY*		
		Pliocene	*Pleion* = more	
		Miocene	*Meion* = less	
		Oligocene	*Oligos* = few	
		Eocene	*Eos* = dawn	

The above terms refer to the proportions of modern shells occurring as fossils in each sub-system

Eras		Periods and Systems	Derivations of Names
MESOZOIC	*Mesos* = middle (Mediæval life)	CRETACEOUS	*Creta* = chalk
		JURASSIC	*Jura* Mountains
		TRIASSIC (NEW RED SANDSTONE)	*Threefold* division in Germany
PALÆOZOIC	*Palaios* = ancient (Ancient life)	PERMIAN (NEW RED SANDSTONE)	*Permia,* anc. kingdom E. of Volga
		CARBONIFEROUS	*Coal-bearing*
		DEVONIAN or	*Devon* (marine sediments)
		OLD RED SANDSTONE	(Land sediments of same period)
		SILURIAN	*Silures,* anc. tribe of Welsh borders
		ORDOVICIAN	*Ordovices,* anc. tribe, N. Wales
		CAMBRIAN	*Cambria* = Wales

PRE-CAMBRIAN ERAS : sometimes described as:

PROTEROZOIC	*Proteros* = Earlier
ARCHÆOZOIC	*Archæos* = Primæval
EOZOIC	*Eos* = Dawn

The term ARCHÆAN refers to the oldest Pre-Cambrian crystalline rocks of a given region

UNRECORDED INTERVAL (duration unknown)

ORIGIN OF THE EARTH

* In 1760 strata were classified as Primitive (crystalline), Secondary (consolidated), and Tertiary (loose). By an extension of this nomenclature, the period in which we

TIME SCALE

Maximum known Thicknesses of Strata in feet		Approximate dates in years	Distinctive Life
		Present day	
Recent / Pleistocene	4,000	25,000	Modern Man
		1,000,000	Stone-Age Man
Pliocene	13,000	15,000,000	Mammals and Flowering Plants
Miocene	21,000	35,000,000	
Oligocene	15,000	50,000,000	
Eocene	14,000	70,000,000	
Cretaceous	64,000	120,000,000	Reptiles
Jurassic	20,000	150,000,000	
Triassic	25,000	190,000,000	
Permian	13,000	220,000,000	Amphibians and Primitive Plants
Carboniferous	40,000	280,000,000	
Devonian *or* Old Red Sandstone	37,000	320,000,000	Fishes
Silurian	15,000	350,000,000	
Ordovician	40,000	400,000,000	Invertebrates
Cambrian	40,000	500,000,000	First appearance of abundant fossils
Proterozoic / Archæozoic / Eozoic	*Unknown in detail but immensely great*		Scanty remains of Sponges and Seaweeds
		at least 1,750,000,000	No direct fossil evidence of Life
Unrecorded Interval			
Origin of the Earth		at least 2,000,000,000	

are now living is called the Quaternary. The Mesozoic era is still sometimes referred to by the term "Secondary."

Provided that the radioactive minerals have remained unaltered since they crystallized, it follows that all minerals with the same lead-ratio are of the same age. When the mineral used is known to have crystallized in an igneous rock or mineral vein at the time when the rock or vein came into existence, its lead-ratio serves to determine the age of the rock or vein. If, in turn, the geological age of the latter is known from its relations towards the associated fossiliferous strata, then the absolute age corresponding to the geological age is also known fairly closely. The time-scale based on the most reliable of the lead-ratios so far determined is given in the table on page 105.

Earth Movements and the Geological Time Scale

As indicated in Fig. 51, great mountain-building movements have been particularly active at certain times in the earth's history, during which the rocks of long belts of the crust were intensely compressed. Earth movements of this kind, and also the resulting folded belts, are described as *orogenic* (Gr. *oros*, a mountain). Mountain building—in the purely structural sense, without reference to the subsequent effects of denudation—is also referred to as *orogenesis*, and a time of mountain building is often called a tectonic or orogenic revolution. Nine such revolutions have already been recognized, three since the Cambrian and six before (see Fig. 52), with long intervals of relative quiescence between each pair, during which thick masses of sediments were accumulated from the denudation of the lands then exposed. We are now living near the close of the orogenic revolution of the Cainozoic era. Ideally, an era can be thought of as a cycle consisting of one of these long intervals (represented by the sediments then deposited) together with the orogenic revolution that brought it to an end (represented by folding of the sediments). Actually, however, the revolutions are not found to be strictly contemporaneous in different parts of the world, and consequently the time divisions so defined for one continent would not coincide exactly with those for other continents.

Orogenic movements are essentially tangential to the crust. Radial movements, in which continental regions are raised or lowered, with little folding, if any, are distinguished as *epeirogenic* (Gr. *epeiros*, a continent). Emergent lands and plateaus result from epeirogenic movements of uplift. Widespread continental areas are uplifted towards the close of each revolution, and the lands then become extensive and locally high, as they are at present. Epeirogenic movements of depression lead to the development of sunken regions, of which the Black Sea and the Mediterranean basins are modern examples.

The marine sediments on the land also record fluctuating changes of level, which no doubt must be largely ascribed to epeirogenic movements. A geological period is characterized by one or more invasions of the land by the sea, during which the marine beds of that particular system were deposited. Each invasion can be divided into (*a*) an advancing phase, as the sea overflows the slowly subsiding lands ; culminating in (*b*) the phase of maximum flooding of the lands ; and (*c*) the phase of retreat of the sea. As an era consists of several periods, it is evident that relative to sea level the lands may rise and fall many times during the interval between successive revolutions. Occasionally it happens, either within a period or towards its close, that retreat of the sea is brought about by orogenic movements on a smaller scale than those referred to as revolutions.

Each revolution or minor orogenesis is recorded in the geological time scale by folding of the rocks, and by the presence of an unconformity between those rocks and the immediately overlying sediments. The geological age of the folding is obviously later than that of the youngest of the folded beds and earlier than that of the oldest beds above the unconformity. Only the last three or four revolutions can be effectively dated in this way. The earlier ones involved beds which cannot be dated by means of fossils, and their ages can therefore be known only from the lead-ratios of radioactive minerals. Fortunately, the latter most commonly occur in granitic rocks that crystallised in the orogenic belts towards the close of each revolution. Consequently, when they do occur, they serve to date the revolution with which they are associated.

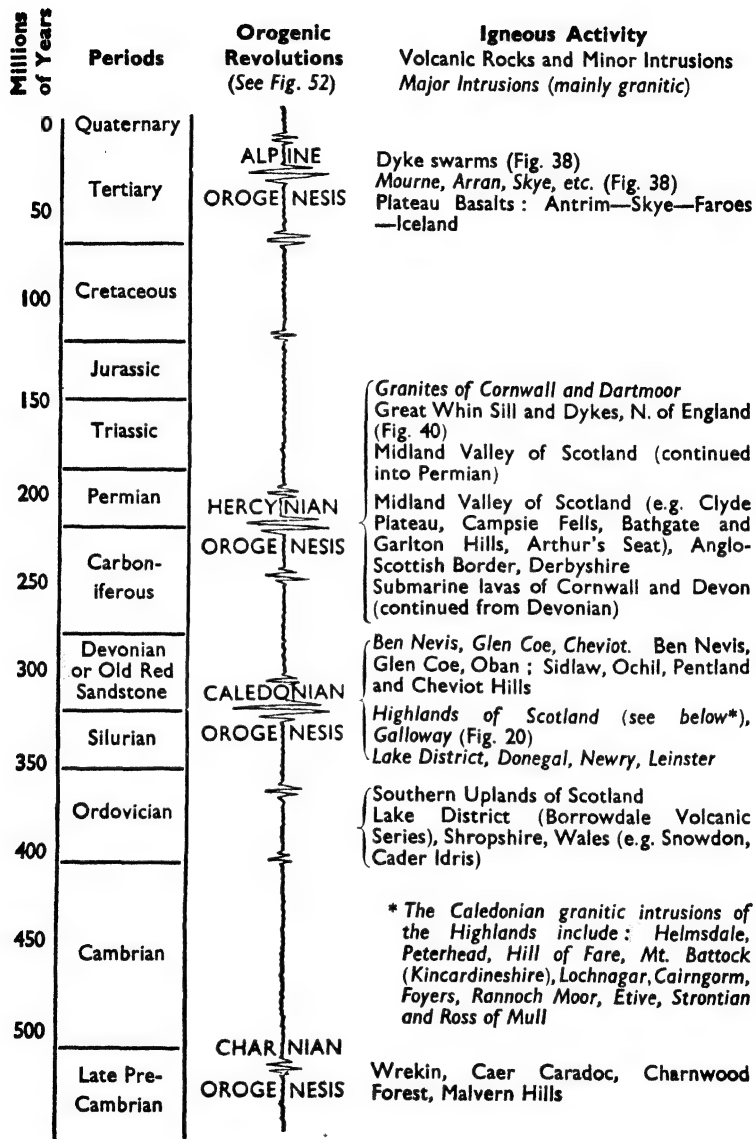



Fig. 51

Diagram to show the ages of the chief European orogenic movements and the chief British occurrences of igneous rocks (since the late Pre-Cambrian)

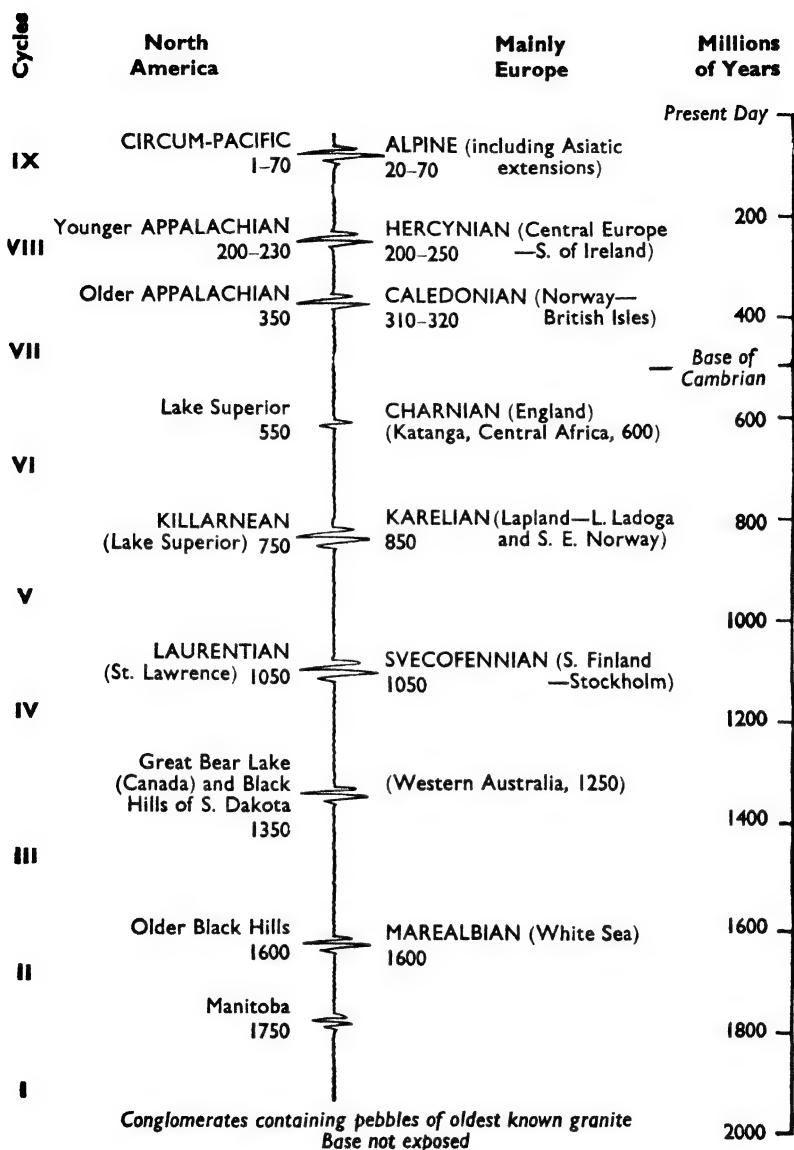



Fig. 52. Diagram to show the chief orogenic revolutions of geological time, with approximate dates in millions of years

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For the study of British Stratigraphy the following map will be found invaluable :

H.M. Geological Survey—*Geological Map of the British Isles.* Scale twenty-five miles to one inch. H.M. Stationery Office, 1939.

PART II EXTERNAL PROCESSES AND THEIR EFFECTS

CHAPTER VIII

ROCK WEATHERING AND SOILS

WEATHERING AND CLIMATE

WEATHERING is the total effect of all the various sub-aerial processes that co-operate in bringing about the decay and disintegration of rocks, provided that no large-scale transport of the loosened products is involved. The work of rain-wash and wind, which is essentially erosional, is thus excluded. The products of weathering are, however, subject to gravity, and there is consequently a universal tendency on the part of the loosened materials to fall or slip downwards, especially when aided by the lubricating action of water. It is, indeed, only through the removal of the products of weathering that fresh surfaces are exposed to the further action of the weathering processes. No clean-cut distinction between weathering and erosion can therefore be attempted.

The geological work accomplished by weathering is of two kinds : (*a*) physical or mechanical changes, in which materials are disintegrated by temperature changes, frost action, and organisms ; and (*b*) chemical changes, in which minerals are decomposed, dissolved, and loosened by the water, oxygen, and carbon dioxide of the atmosphere, and by organisms and the products of their decay. The physical, chemical, and biological agents actively co-operate with one another. Shattering requires stresses powerful enough to overcome the strength of the materials, but the latter is generally greatly reduced by the preliminary action of decomposition. Shattering in turn provides increased opportunities for the further penetration of the chemical agents. Everywhere full advantage is taken of

the joints and bedding planes which, together with the cracks newly formed, admit air, water, and rootlets down to quite considerable depths. Thus, although the processes of weathering may be considered separately, it must not be forgotten that the actual work done is the resultant effect of several processes acting together in intimate co-operation.

The materials ultimately produced are broken fragments of minerals and rocks ; residual decomposition products, such as clay ; and soluble decomposition products which are removed in solution. The products of weathering differ widely in different places according to the climatic conditions and the relief and configuration of the surface. In general it may be said that disintegration is favoured by steep slopes and by the conditions characteristic of frost-ridden or desert regions, while decomposition and solution are favoured by low relief and by humid conditions, especially in tropical regions. In the temperate zones the weather is widely variable, and most of the leading processes are to be found in operation during one part of the year or another.

Disintegration by Temperature Changes

Frost is an irresistible rock breaker. When water fills cracks and pores and crevices in rocks and then freezes, it expands by ten per cent. of its volume, and exerts a bursting pressure of about 2,000 lb. to the square inch. The rocks are ruptured and fragments are wedged apart, to become loose when thaw sets in. Steep mountain slopes and cliffs are particularly prone to destruction in this way, especially where joints are plentiful. The frost-shivered fragments fall to lower levels, and accumulate there as *screes* of angular debris (Plates 22 and 23A). Above, the ragged sky-line rises out of the ruins. The screes of Wastwater, the flying buttresses of Snowdon (Plate 54B), and the great pyramid of the Matterhorn (Plate 50) are familiar witnesses to the quarrying power of frost. For a time the screes protect the lower slopes, but their permanent accumulation is prevented by landslides and avalanches,

transport by rivers and glaciers, and coast erosion by the sea. In sub-arctic regions wide shore-platforms are produced by the co-operation of the waves with melting snow and frost in their ceaseless attack on the cliffs (Fig. 154).

In arid climates the rocks exposed to the blazing sun become intensely heated, and in consequence an outer shell expands and tends to pull away from the cooler layer a few inches within. If the rocks are appropriately bedded or jointed, actual separation of a curved shell readily takes place. If the rocks are massive, they must first be weakened by chemical weathering, but sooner or later rupture occurs. When the rocks cool down again, the resulting contraction is relieved by the development of cracks at right angles to the surface. This part of the process is facilitated by rapid chilling due to sudden rainstorms, for in the rare downpours of desert regions the rain may be near freezing-point, and even hail-stones are not unknown. Shells and flakes of rock are thus set free and broken down into smaller fragments. The disintegration of pebbles is often conspicuous (Plate 23B). Individual minerals swell and shrink and gradually crumble apart, especially in coarse-grained rocks like granite. Even in temperate regions the effect of the sun is far from negligible. Building stones exposed to the sun are found to decay much more rapidly than those facing north or otherwise in the shade.

In desert and semi-arid regions and in monsoon lands with a marked dry season a characteristic effect on the outlines of upstanding hillocks and peaks, especially where they are made of crystalline rocks, is produced by *exfoliation*, the peeling off of curved shells of heated rock. At edges and corners the ruptures are particularly curved, because there the increase of temperature penetrates more deeply into the rock than where flat surfaces are exposed. Sharp corners and projecting knobs are the first to fall away, rounded outlines are developed, and the hills become dome-shaped. On convex slopes, successive shells may be seen, overlapping like the tiles on a roof, each ready to fall away as soon as it is liberated by the formation of radial cracks. This effect is well seen in the *inselbergs* (isolated " island " mounts) of Mozambique and other parts

[G. P. Abraham, Ltd., Keswick

Screes of Doe Crag (Borrowdale Volcanic Series), Old Man of Coniston, Lake District

PLATE 23

[*L. Hawkes*

(A) Screes from the Tertiary igneous rocks (granophyre and gabbro) of Austerhorn, Iceland

[*J. J. H. Teall*

(B) Desert surface near the Pyramids, Cairo, showing pebbles shattered by temperature changes

of Africa (Fig. 144 and Plate 65A). Sometimes after sunset the loud report of a splitting rock and the noise of its fall down the mountain side can be heard.

THE RÔLE OF ANIMALS AND PLANTS

Earthworms and other burrowing animals such as rodents and termites play an important part in preparing material for removal by rain-wash and wind. Worms consume large quantities of earth for the purpose of extracting food, and the indigestible particles are passed out as worm-casts. In an average soil there may be 150,000 worms to the acre, and in the course of a year they raise ten to fifteen tons of finely comminuted materials to the surface.

The growing rootlets of shrubs and trees exert an almost incredible force as they work down into crevices. Cracks are widened by expansion during growth (Plate 4B) and wedges of rock are forcibly shouldered aside. Plants of all kinds, including fungi and lichens, also contribute to chemical weathering, since they abstract certain elements from rock materials. Moreover, water containing bacteria attacks the minerals of rocks and soils much more vigorously than it could do in their absence. The dead remains of organisms decay in the soil largely as a result of the activities of bacteria and fungi. In this way carbon dioxide and organic acids, together with traces of ammonia and nitric acid, are liberated, all of which increase the solvent power of soil-water. The chief organic product is a " complex " of brown jelly-like substances collectively known as *humus*. Humus is the characteristic organic constituent of soil, and water containing it can dissolve small amounts of certain substances, such as limonite, which are ordinarily insoluble.

Another effect of vegetation, one which is of vital importance in the economy of nature, is its protective action. Rootlets bind the soil into a woven mat so that it remains porous and able to absorb water without being washed away. The destructive effects of rain and wind are thus effectively re-

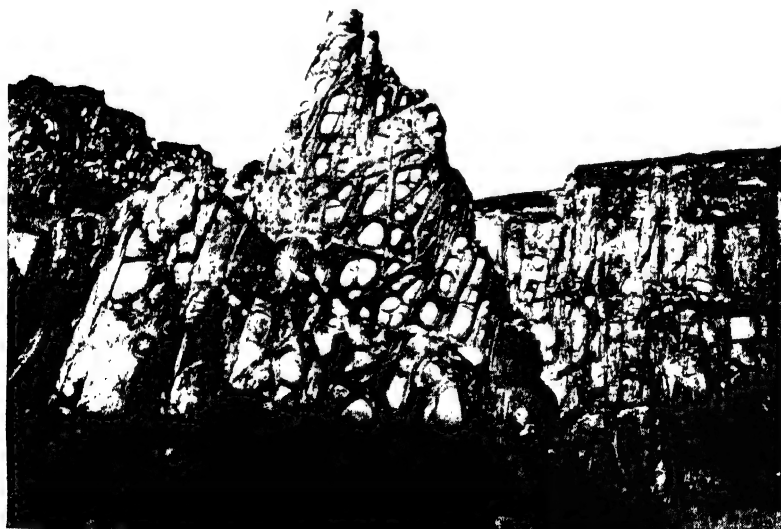
strained. Forests break the force of the rain and prevent the rapid melting of snow. Moreover, they regularize the actual rainfall and preclude the sudden floods that afflict more sterile lands. For these reasons the reckless removal of forests may imperil the prosperity of whole communities. Soil erosion is intensified, agricultural lands are impoverished and lost, and barren gullied wastes, like the " badlands " of North America, take their place (Plates 32B and 63A). Except after heavy rainfall, the rivers run clean in forested lands, but after deforestation their waters become continuously muddy. Destruction of the natural vegetation by land clearing and ploughing, and the failure to replace forests cut down for timber or destroyed by fire, have had disastrous economic consequences in many parts of Africa and America. Man himself has been one of the most prodigal of the organic agents of destruction.

Chemical Weathering

The alteration and solution of rock material by chemical processes is largely accomplished by rain-water acting as a carrier of dissolved oxygen and carbon dioxide, together with various acids and organic products derived from the soil. The degree of activity depends on the composition and concentration of the solutions so formed, on the temperature, on the presence of bacteria, and on the substances taken into solution from the minerals decomposed. The chief changes that occur are solution, oxidation, hydration, and the formation of carbonates. Only a few common minerals resist decomposition, quartz and muscovite (including sericite) being the chief examples. Others, like the carbonate minerals, can be entirely removed in solution. Most silicate minerals break down into insoluble residues, such as the various clay minerals, with liberation of soluble substances which are removed in solution.

Limestone is scarcely affected by pure water, but when carbon dioxide is also present the $CaCO_3$ of the limestone is slowly dissolved and removed as calcium bicarbonate, $Ca(HCO_3)_2$. The harsh limestone platforms around Settle

[H.M. Geol. Survey

(A) Chemical weathering of Great Scar Limestone (Carboniferous) with formation of clints, above Malham Cove, Yorkshire (*cf.* Plate 8B)

[H.M. Geol. Survey

(B) Spheroidal weathering of dolerite sill, North Queensferry, Fife

[*H.M. Geol. Survey*

(A) Production of residual boulders of dolerite by spheroidal weathering, North Queensferry, Fife

[*C. T. Trechmann*

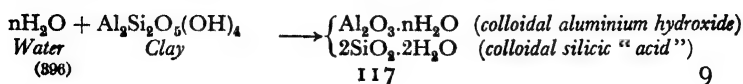
(B) Residual boulders of granite on an exfoliated surface of granite, Matopo Hills, Southern Rhodesia

and Ingleborough have deeply grooved and furrowed surfaces which clearly show the effects of solution. All the joints are widened into " grikes," and the bare surface is free from soil, except where a little wind-blown dust has collected in the crevices (Plate 24A). When limestone contains impurities such as quartz and clay, these remain undissolved, and so accumulate to form the mineral basis of a soil. The red earths, known as *terra rossa*, that cover the white limestones of the Karst, a plateau behind the Adriatic coast of Yugoslavia, are weathering residues rich in insoluble iron hydroxides derived by long accumulation from the minute traces of iron compounds in the original limestone.

Clay minerals are the chief residual products of the decomposition of felspars. Under the action of slightly carbonated waters the felspars break down in the following way :

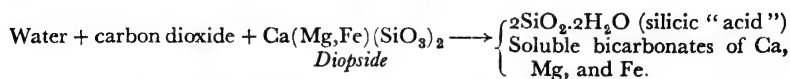
$$\underset{\text{Water}}{6H_2O} + CO_2 + \underset{\text{Orthoclase}}{2KAlSi_3O_8} = \begin{cases} Al_2Si_2O_5(OH)_4 \ \textit{(a clay mineral)} \\ 4SiO_2.4H_2O \ \textit{(silicic "acid")} \\ K_2CO_3 \ \textit{(removed in solution)} \end{cases}$$

From plagioclase the products are similar, except that Na_2CO_3 is formed from albite and $Ca(HCO_3)_2$ from anorthite (in place of K_2CO_3). Most of the clay is probably at first in the colloidal state, that is to say, it consists of minute particles dispersed through water, the particles being much larger than atoms but much smaller than any that can be seen with a microscope. The particles may coagulate into an amorphous clay mineral or crystallise into tiny scales or flakes. The alkalies easily pass into solution, but whereas soda tends to be carried away, to accumulate in the sea, potash is largely retained in the soil. It is withdrawn from solution by colloidal clay and humus, from which in turn it is extracted by plant roots. When the plants die the potash is returned to the soil. Analyses of river waters show that very little ultimately escapes from the lands.

As a result of certain obscure reactions, still not cleared up in detail, colloidal forms of clay break down still further :

$$\underset{\text{Water}}{nH_2O} + \underset{\text{Clay}}{Al_2Si_2O_5(OH)_4} \longrightarrow \begin{cases} Al_2O_3.nH_2O \ \textit{(colloidal aluminium hydroxide)} \\ 2SiO_2.2H_2O \ \textit{(colloidal silicic " acid ")} \end{cases}$$

In the humid conditions of the temperate zone aluminium hydroxide is not liberated to any important extent, but during the dry season of tropical and monsoon lands it is precipitated in a highly insoluble form, and so accumulates at or near the surface as bauxite (see page 120).

The decomposition of the ferromagnesian minerals may be illustrated by reference to the simplest type of pyroxene :

$$\text{Water} + \text{carbon dioxide} + \underset{\textit{Diopside}}{Ca(Mg,Fe)(SiO_3)_2} \longrightarrow \begin{cases} 2SiO_2.2H_2O \text{ (silicic "acid")} \\ \text{Soluble bicarbonates of Ca,} \\ \quad \text{Mg, and Fe.} \end{cases}$$

When Al_2O_3 and Fe_2O_3 are also present (as in biotite and all varieties of augite and hornblende) clay and chloritic minerals and limonite remain as residual products. In the presence of oxygen limonite is also precipitated from solutions containing $Fe(HCO_3)_2$. For this reason weathered rock surfaces are commonly stained a rusty brown colour. Ordinary rust is, in fact, the corresponding product of the action of water and air on iron and steel.

Chemical weathering contributes to the disintegration of rocks (*a*) by the general weakening of the adhesion between minerals, so that the rock more readily succumbs to the attack of the physical agents ; (*b*) by the formation of solutions which are washed out by the rain, so that the rock becomes porous and ready to crumble (*e.g.* the liberation of the grains of a sandstone by solution of the cement) ; and (*c*) by the formation of alteration products with a greater volume than the original fresh material, so that (as in exfoliation) the outer shell swells and pulls away from the fresh rock within.

The separation of shells of decayed rock is distinguished as *spheroidal weathering* (Plate 24B). It is best developed in well-jointed rocks which, like many basalts and dolerites, are readily decomposed. Water penetrates the intersecting joints and thus attacks each separate block from all sides at once. As the depth of decay is greater at corners and edges than along flat surfaces, it follows that the surfaces of rupture become rounded in such positions. As each shell breaks loose, a new surface is presented to the weathering solutions, and the process is repeated again and again, aided in the appropriate regions

by frost. Each successive wrapping around the fresh core becomes more nearly spheroidal than the one before, until ultimately the angular block is transformed into an onion-like structure of concentric shells of rusty and thoroughly rotted residual material, with perhaps a round and coherent core of fresher rock still left in the middle. Such cores may stand out like boulders when their soft outer wrappings have been washed away by the rain (Plate 25).

Weathering Residues

In dry climatic regions, on steep rock-slopes, and over massive crystalline rocks, the coating of chemically weathered material may not become more than a thin film. But where rain- and soil-water can soak deeply into the rocks, weathering may proceed to a considerable depth. In the Malay States, where the rainfall is heavy and evenly distributed, granite has been converted into soft friable earth to depths of as much as fifty feet. In tropical regions which have a heavy rainfall during the wet season, succeeded by a dry season, when the temperature is high and evaporation rapid, the weathering residues may be very different. Soil-water is removed by plants, and water from below is drawn up to make good the loss so long as the supply holds out. The weak solutions produced by leaching of the rocks during the wet season thus become concentrated by evaporation, and the dissolved materials are deposited, the least soluble being the first to be precipitated. The products include hydroxides of aluminium and iron, silica, and various carbonates and sulphates. Most of these are re-dissolved by the rains of the next wet season, but as the hydroxides of aluminium and iron are left in a highly insoluble state, they remain at or near the surface, and gradually accumulate as a reddish brown deposit to which the name *laterite* has been given (L. *later*, a brick). In depth the material is variegated and paler in colour, and it is here that alumina tends to be specially concentrated. At greater depths the bed-rocks may be intensely decomposed, with abundant development of clay minerals.

Sheets of laterite rarely become thick—30 feet is exceptional—because, being impervious, their very formation puts an end to the drainage which is essential to their continued growth. For this reason, too, the overlying soil becomes infertile, and then, no longer held together by roots, it is easily scoured away by torrential rains, leaving large sterile exposures of laterite. In certain regions, as in parts of India, laterite is found to be quite soft below its hard and slag-like crust. The soft laterite can be readily cut into bricks which set hard on exposure to the sun. This easily worked and valuable building material was called laterite not because it resembles brick, but because bricks are made from it.

Quartz, and clay minerals that have not suffered the ultimate loss of silica, remain cemented in the deposit in various proportions. There is every possible gradation between quartz (the chief mineral of sand), clay (mainly composed of clay minerals), and laterite, as indicated by the following scheme :

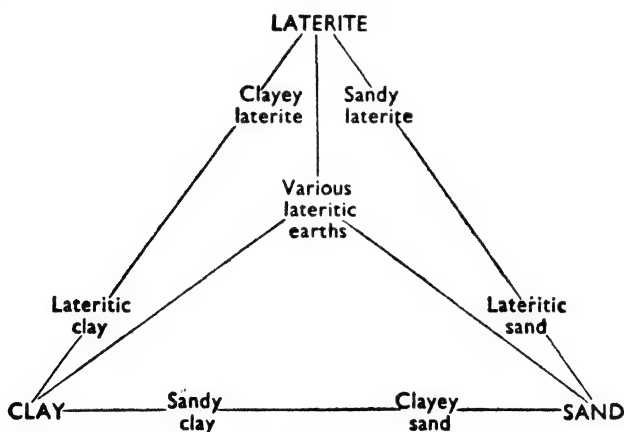



FIG. 53

Of the laterites themselves, two important varieties are distinguished : those rich in iron and those rich in aluminium. The latter, when of high grade, constitute bauxite, the only ore of aluminium from which it is practicable to extract the metal on a commercial scale.

The Mantle of Rock-Waste

The superficial deposits which lie on the older and more coherent bedrocks form a mantle of rock-waste of very varied character. In many places the mantle lies directly on the bedrock from which it was formed by weathering. In this case quarry sections and cuttings of all kinds generally show a surface layer of *soil*, passing gradually downwards through a zone of shattered and partly decomposed rock, known as the *subsoil*, to the parental bedrock, still relatively fresh and unbroken by weathering agents. In the soil vegetable mould and humus occur to a varying extent, and under appropriate conditions they accumulate to form thick beds of peat which must also be regarded as part of the mantle. Soils develop, however, not only on bedrock, but also on a great variety of loose deposits transported into their present positions by gravity, wind, running water, or moving ice. Although these deposits will not be considered in detail till later, it is convenient to summarise them here, according to their mode of origin, together with the untransported or *sedentary* deposits of the mantle.

THE MANTLE OF ROCK-WASTE
(Continental deposits)

Mode of Origin		*Characteristic Deposits*
SEDENTARY		
Essentially inorganic	*Residual*	Gravels, sands, and clays. *Terra rossa*, lateritic earths and laterite
Inorganic and organic	*Soils*	Including soils on bedrock and on mantle deposits
Essentially organic	*Cumulose*	Vegetation residues : swamp deposits and peat
TRANSPORTED		
By Gravity	*Colluvial*	Screes and landslip deposits
,, Wind	*Æolian*	Sand dunes, sand wastes, and loess
,, Ice	*Glacial*	Boulder clay, moraines, and drumlins
,, Melt-water from ice	*Glaciofluvial*	Outwash fans, kames, and eskers
,, Rivers (deposited in lakes)	*Lacustrine*	Alluvium and saline deposits
,, Rivers	*Fluviatile*	Alluvium, passing seawards by way of *Estuarine* or *Deltaic* deposits into *Marine* deposits

The Growth and Nature of Soils

As Grenville Cole has finely said : " The soil, considered as a rock, links common stones with the atmosphere, and the dead dust of the earth with the continuity of life." The purely mineral matter of the residual or transported deposits is first colonised by bacteria, lichens, or mosses. By the partial decay of the dead organisms mould and humus (see p. 115) begin to accumulate ; lodgment is afforded for ferns and grasses ; berries and winged seeds are brought by birds and the wind ; and finally shrubs and trees may gain a footing. The rootlets work down, burrowing animals bring up inorganic particles, and the growing mass becomes porous and sponge-like, so that it can retain water and permit the passage of air. Frost and rain play their parts, and ultimately a mature soil, a complex mixture of mineral and organic products, is formed. But though the soil is a result of decay, it is also the medium of growth. It teems with life, and as the source of supply of nearly all food it is for mankind the most valuable and least dispensable of all his natural assets.

Soil may be defined as the surface layer of the mantle of rock-waste in which the physical and chemical processes of weathering co-operate in intimate association with biological processes. All of these processes depend on climate, and in accordance with this fact it is found that the resulting soils also depend on the climate in which they develop. Other factors are also involved : particularly the nature of the bed-rock or other deposit on which the soil is generated, the relief of the land, the age of the soil (that is, the length of time during which soil development has been in progress), and the super-imposed effects of cultivation.

The influence of the parental material is easily understood. Sand makes too light a soil for many plants, as it is too porous to hold up water. Clay, on the other hand, is by itself too impervious. A mixture of sand and clay makes a *loam,* which avoids these extremes and provides the basis of an excellent soil. A clay soil may also be lightened by adding limestone,

and the natural mixture, known as *marl*, is also a favourable basis. Limestone alone, as we have seen, cannot make a soil unless it contains impurities. In most climates granite decomposes slowly and yields up its store of plant foods very gradually. Basaltic rocks, on the other hand, break down much more quickly. Lavas provide highly productive soils which, even on the flanks of active volcanoes, such as Etna, compensate the agriculturist and vine-grower for the recurrent risk of danger and possible destruction.

These differences are most marked in young soils and in temperate regions. As the soil becomes older, and especially when the climate is of a more extreme type, the influence of long continued weathering and organic growth and decay makes itself felt more and more. Certain ingredients are steadily leached out, while others are concentrated. Humus accumulation depends on the excess of growth over decay, and this in turn depends on climatic factors. The composition of the evolving soil thus gradually approaches a certain characteristic type which is different for each climatic region. The black soil of the Russian steppes, for example, is equally well developed from such different parent rocks as granite, basalt, loess, and boulder clay. Conversely, a single rock type, like granite, gives grey soils in temperate regions (*podsol*), black soils in the steppes (*chernosem*), and reddish soils in tropical regions of seasonal rainfall (*lateritic earths*). The colours of soils are almost wholly due to the relative abundance (or paucity) of various iron compounds and humus.

Deeply cultivated soils may be more or less uniform throughout, but this is not the case in purely natural soils. A vertical cutting through an old natural soil reveals a characteristic layered arrangement which is called the *soil profile.* The latter is clearly developed in the grey soils of the more or less forested north-temperate belt of Canada, Northern Europe, and Asia. As the drainage is dominantly descending, iron hydroxides, and humus derived from the surface layer of vegetable mould, are carried down in colloidal solution. Thus a bleached zone is developed, and for this reason the soil type is called *podsol* (Russian, ashy grey soil). By the accumulation

CLIMATIC SOIL TYPES AND ASSOCIATED DEPOSITS

Climatic Regions		Characteristic Vegetation	Mainly Organic	Mixed Organic and Inorganic	Mainly or Entirely Inorganic
POLAR	Ice Caps	—	—	—	—
	Tundras (short mild summer)	Mosses and Lichens	Peat Soils Peat	Frost-shattered Stony Soils	
TEMPERATE HUMID	Boreal (cold winter)	Forests	Peat Soils Peat	PODSOL (Grey)	
	Temperate (mild and humid)	Forests and varied	Peat Soils Peat	PODSOL (Grey) Grey Forest Earths	
	Mediterranean (short mild winter)	Evergreen Shrubs and Trees		Brown Forest Earths	*Terra Rossa*
ARID and SEMI-ARID	Steppes (dry summer)	Grasses		CHERNOSEM (Black) Chestnut-brown soils —Grey Marginal Soils—	
	Deserts	Marginal Scrub — Marginal Scrub			White Salt Encrustations Desert Sands White Salt Encrustations
TROPICAL RAINY	Savannahs (wet and dry seasons)	Grasses and Parklands		—Grey Marginal Soils— Brown Soils Black Soils	Laterite
	Monsoon Lands (wet and dry seasons)	Forests	Swamp Soils Peat	Brown Lateritic Earths Red Lateritic Earths	LATERITE (Red—Reddish and Brown)
	Equatorial (continuously humid)	Evergreen Rain Forests	Swamp Soils Peat	Brown Earths Grey Bleached Earths	

of the ferro-humus material at a depth of a few inches or a foot, accompanied by particles of silt and clay washed down mechanically, a deep brown or nearly black layer of variable thickness is formed. This may develop into a hard, well cemented band, impervious to drainage, which is known as *hard pan*. One of the objects of ploughing is to prevent the growth of hard pan. Otherwise, water-logged conditions may set in, and there will then be a marked tendency for peat to accumulate.

Farther south in the grasslands of the steppes and prairies, summer drought and winter frosts favour the accumulation of humus, largely provided by the grass roots which die each year. During the dry season ground-water is drawn towards the surface, and $CaCO_3$ is precipitated, often in irregular nodules, at a depth of two or three feet. Under the influence of the ascending calcareous solutions the humus becomes black and insoluble. Iron hydroxides are therefore not leached out as in the podsol. The upper layer of the soil profile is black, becoming brown in depth where the humus content is less. For this reason the soil type is called *chernosem* (Russian, black earth). The black cotton soils of India and the " black bottoms " of the Mississippi flood plains are of similar origin.

SUGGESTIONS FOR FURTHER READING

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CHAPTER IX

UNDERGROUND WATERS

SOURCES OF GROUND-WATER

THERE is abundant evidence for the existence of important underground supplies of water. At least from the time of the Babylonians there was a widespread and firmly held belief that not only springs and wells, but also rivers, were fed and maintained by water from vast subterranean reservoirs. The underground streams of limestone caverns supported this belief, and so did the spurting up of " the fountains of the deep " through fissures riven in alluvial flats by earthquakes. Moreover, in arid countries like Mesopotamia and Egypt it was far from obvious that rivers could be maintained by rainfall. The author of Ecclesiastes remarked that although " the rivers run into the sea, yet the sea is not full," and inferred that the balance was restored by a return circulation, underground from the sea floor, back to the sources of the rivers. How the sea water rose to such high levels was not explained, and how it lost its salt before emerging as springs of freshwater remained an unsolved problem. It was only late in the seventeenth century that it first came to be realized, notably by Halley, that the circulation from sea to rivers was not underground, but through the atmosphere by way of evaporation and rainfall. Aristotle's erroneous conviction that the rainfall was quite inadequate to supply the flow of rivers was not dispelled until accurate measurements took the place of mere opinion. In 1674 Pierre Perrault completed the first quantitative investigation of the relation between rainfall and stream flow. He found that in the upper valley of the Seine the rainfall was actually several times greater than the stream flow, and so demonstrated for the first time a relationship that in humid climates seems now to be almost a matter of common sense.

The following scheme shows the various ways in which rainwater is distributed (see also Fig. 7, page 22) :

Run-off	Direct flow down surface slopes	Stream Flow
Percolation	Superficial flow through soil and sub-soil to streams	Stream Flow
Percolation	Downward infiltration into bedrocks to replenish the ground-water and maintain its circulation	Ground-water
Percolation	Absorption by soil and vegetation, subsequently evaporated	Evaporation
Direct Evaporation		Evaporation

(During weathering a relatively trifling amount of water is fixed by hydration in clay minerals and other weathering products.)

Ground-water supplied by rain or snow or by infiltration from rivers and lakes is described as *meteoric*. Fresh or salt water entrapped in sediments during their deposition is distinguished as *connate*. During burial and compaction of the sediments, much of this fossil water is expelled, and during metamorphism most of it is driven out, carrying with it dissolved material which helps to cement the sediments at higher levels. Steam and hot mineral-laden water liberated during igneous activity, and believed to reach the surface for the first time, is known as *juvenile* water.

The Storage and Circulation of Ground-water

Below a certain level, never far down in humid regions, all porous and fissured rocks are completely saturated with water. The upper surface of this ground-water is called the *water table*. The water table is arched up under hills, roughly following the relief of the ground, but with a more subdued surface. In general, three successive zones may conveniently be recognised (Fig. 54) :

(*a*) *The zone of non-saturation*, which is never completely filled, but through which the water percolates on its way to the underlying zones. A certain amount of water is retained by the soil, which yields it up to plant roots.

(*b*) *The zone of intermittent saturation*, which extends from the highest level reached by ground-water after a period of

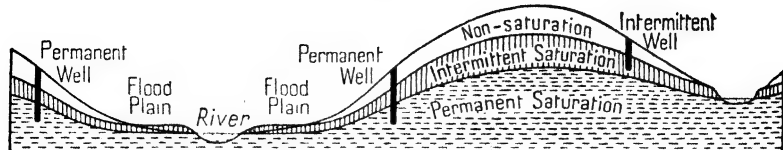



FIG. 54

To illustrate the relation of the water table to the surface and its variation of level from the top to the bottom of the zone of intermittent saturation after prolonged periods of wet and dry weather respectively

prolonged wet weather, down to the lowest level to which the water table recedes after drought.

(*c*) *The zone of permanent saturation*, which extends downwards to the limit beneath which ground-water is not encountered. The depths in mines and borings at which the rocks are found to be dry vary very considerably according to the local structures, but a limit of the order 2,000 to 3,000 feet is not uncommon. Juvenile and expelled connate water may, of course, ascend from much greater depths.

Wherever the zone of permanent saturation rises above ground level, seepages, swamps, lakes, or rivers occur. When the zone of intermittent saturation temporarily reaches the surface, floods develop and intermittent springs appear. Conversely, many springs and swamps, and even the rivers of some regions, go more or less dry after long periods of dry weather when the water table falls below its usual level.

Rocks through which water can pass freely are said to be *pervious*. They may be porous and *permeable*, like sand and sandstone ; or they may be practically non-porous and impermeable, like granite, but nevertheless pervious because of the presence of interconnected open joints and fissures through which water can readily flow. Impervious rocks are those through which water cannot easily soak ; they may be of two kinds : porous, like clay, or relatively non-porous, like massive unfissured granite. It should be noticed that although porosity is essential in order that a formation can be readily permeable by water, it is not a sufficient condition. The size and arrangement of the openings must also be such that continuous through-channels for the free passage of water

are available. In clays there are no continuous passage-ways wide enough to permit the flow of water, except by slow capillary creep.

Ordinary sand or gravel has a porosity of about 35 per cent. (*i.e.* the material in bulk is made up of 35 per cent. of " voids " and 65 per cent. of " solids "), but this drops to about 15 per cent. in common sandstones, according to the degree of compaction and the amount of cementing material. Clay, although it is impervious, may have a porosity of over 45 per cent. By compaction under pressure and the squeezing out of water the porosity drops gradually, falling to as little as 5 per cent. in some shales, and to 3 per cent. in slates. In limestones the porosity ranges from 30 per cent. in friable chalk to 5 or less in indurated and recrystallised varieties. Limestone, however, may carry a great deal of water in joints and other channels (including caves) opened out by solution. The porosity of massive igneous and metamorphic rocks is generally less than 1 per cent., but here again water may circulate in appreciable quantities through the passage-ways afforded by interconnected joints and fissures.

Alternations of pervious and impervious strata, especially when folded, faulted, and jointed, form underground reservoirs and natural waterworks of great variety. Where the catchment area is sufficiently high the water slowly migrates through the most pervious formations towards places at a lower level where the water can escape to the surface. It may emerge through natural openings (seepages and springs) or through artificial openings (wells), or it may feed directly into rivers or lakes or even discharge through the sea floor. The sustained flow of rivers which, like the Nile, successfully cross wide stretches of desert is to some extent due to supplies received from underground sources.

Springs and Wells

When rainwater sinks into a pervious bed, such as sandstone, it soaks down until it reaches an underlying impervious bed, such as clay or shale. If the surface of the junction is

inclined, the water flows down the water-tight slope, to emerge where the junction is intercepted by a cliff or valley side (Fig. 55*a*). A general oozing out of the water along the line of interception is called a seepage. More commonly a line of

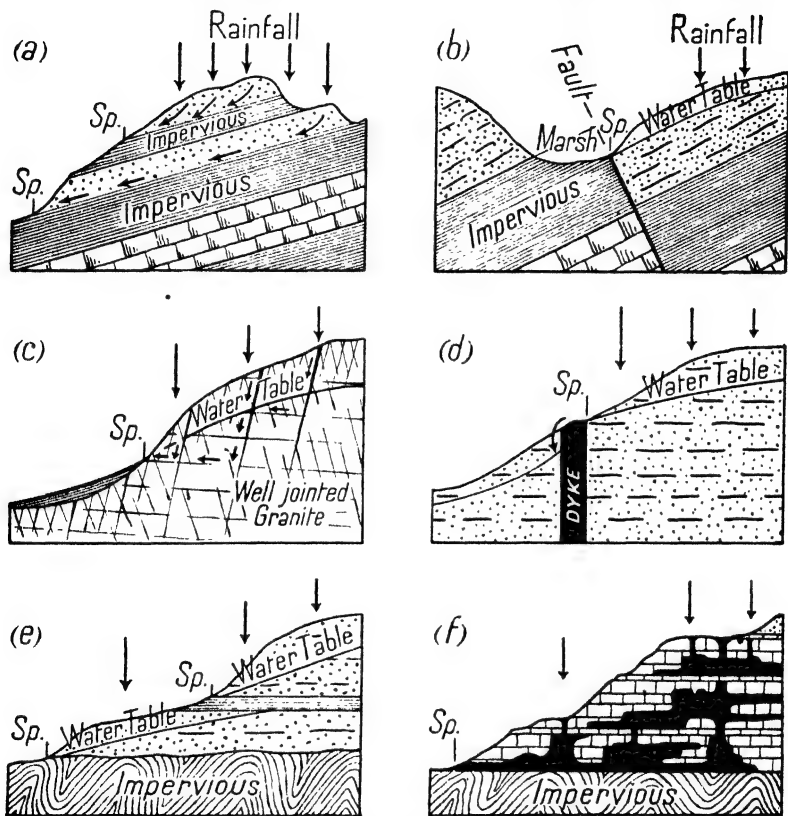



FIG. 55

To illustrate various conditions giving rise to springs (see text)

localised springs appears. The other diagrams of Fig. 55 illustrate various examples of other structures favouring the development of springs. In (*b*) a fault brings pervious sandstone against shale which, being impervious, holds up the water. Springs are localised along the line of the fault, and the low ground on the left is marshy. In (*c*) water enters the joints

in a massive rock, such as granite, and issues in appropriate places. In (*d*) water impounded by a dyke escapes along the outcrop of the junction. In (*e*) the upper spring is thrown out by a conformable bed of shale, as in (*a*) ; the lower spring appears at the outcrop of an unconformity, the underlying folded rocks being impervious. In (*f*) water enters jointed limestone, widens the joints by solution, forming caves and underground channels down to the impervious base of the formation. The latter holds up the water and allows it to drain out, sometimes as an actual stream, where a valley has

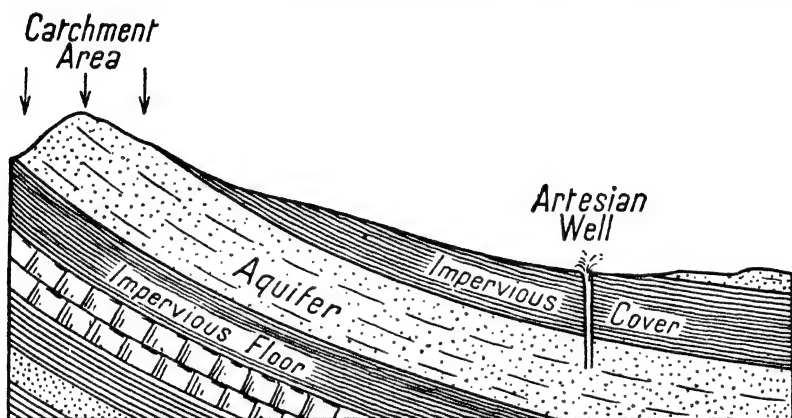



Fig. 56
To illustrate the structural conditions favourable to artesian wells

been excavated through the limestone into the underlying rocks.

Wells are simply holes dug or bored or drilled into the ground to a depth at which water-bearing permeable formations or fissured rocks are encountered. Shallow wells, as shown in Fig. 54, may dry up at certain seasons, unless they tap the zone of permanent saturation. Ground-water percolates into the bottom of the well, and rises to a level that depends on the head of pressure behind it. Pumping or lifting may be necessary to bring the water to the surface. In selecting sites for shallow wells special precaution is necessary to preclude contamination by germ-laden water which might drain into

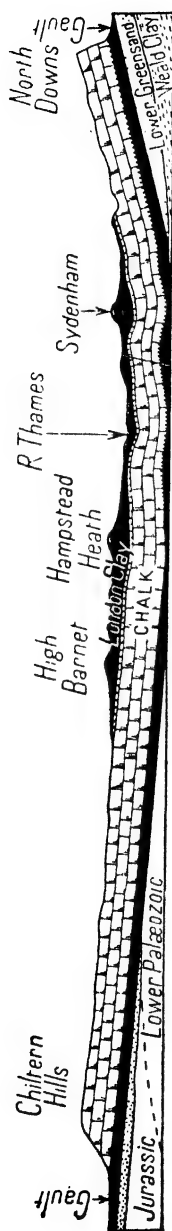



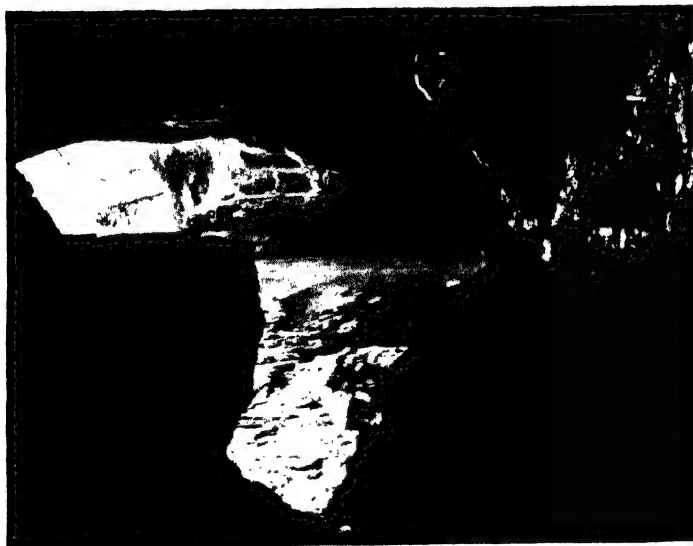
Fig. 57

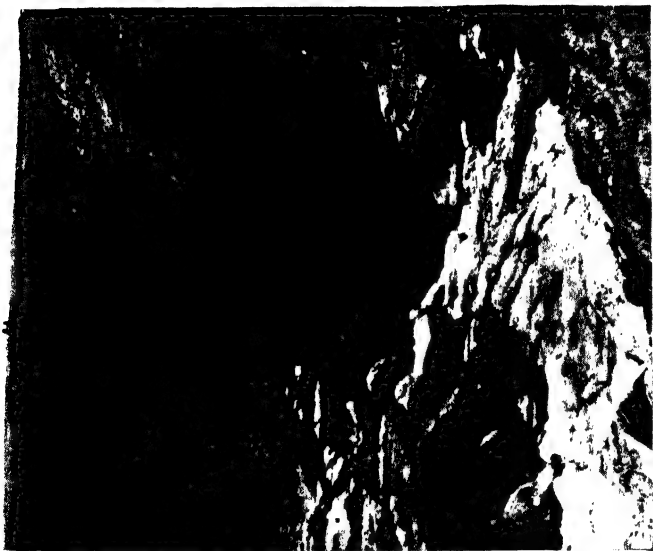
Section across the London Basin. Length of section equals 58 miles

the source of supply from farmyards and cesspools. The ground-water from more deep-seated formations is preferable for human consumption, as it is more likely to be free from the dangers of surface contamination.

Artesian wells are those in which the water encountered in depth is under a sufficient hydraulic pressure to force it to overflow at the surface. The necessary conditions are: (*a*) an inclined or broadly synclinal water-bearing formation, or *aquifer*, enclosed on both sides by watertight beds; (*b*) exposure of the rim of the aquifer over a catchment or intake area at a sufficient height to provide a hydraulic head at a level above the ground where the wells are sunk; (*c*) a sufficient rainfall to furnish an adequate supply of water; and (*d*) absence of a ready means of escape of the water except through the wells. The term *artesian* is sometimes extended to include deep wells in which the water approaches the surface but does not actually reach it.

The London Basin (Fig. 57) exemplifies these conditions very clearly. The aquifer is the Chalk, with sandy beds above and, locally, below. The enclosing impervious formations are the London clay above and the Gault clay below. Water falling on the Chalk, where it is exposed along the Chilterns to the north, and the North Downs to the south, sinks into the basin and accumulates there—or did so until the original resources became impoverished by the insatiable thirst of London. The water

[*E.N.A.*

(A) Alum Pot, Horton Slopes of Ingleborough

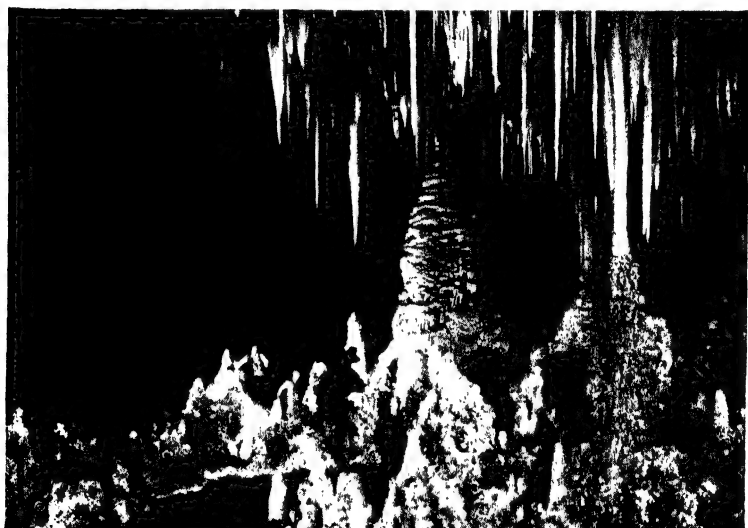
[*Flatters and Garnett*

(B) Gaping Ghyll, south-eastern slopes of Ingleborough

SWALLOW HOLES, YORKSHIRE

PLATE 27

[*W. T. Lee, U.S. Geol. Survey*

(A) "Totem Poles" in the Big Room, Carlsbad Cavern, New Mexico

[*E.N.A.*

(B) The King's Chamber, Carlsbad Cavern, New Mexico

STALACTITES AND STALAGMITES

in the Chalk is tapped in the London area by hundreds of wells sunk to depths up to 600 or 700 feet. Up to a century ago the Chalk was saturated, and when the fountains in Trafalgar Square were first constructed the water gushed out well above the surface. In more recent years the enormous supplies which have been drawn from the Chalk reservoir have exceeded replenishment by rainfall on the rims of the basin. The level of the water in the Chalk has therefore fallen, and water can now be raised to the surface only by pumping.

In North and South Dakota an important aquifer dips off the edge of the Black Hills, and carries a copious supply of water beneath the plains to the east. Over an area of 15,000 square miles the water can be tapped by artesian wells. The largest artesian basin in the world is that of Queensland and adjoining parts of New South Wales and South Australia. The catchment area is in the Eastern Highlands where a widespread series of soft Jurassic sandstones come to the surface. These sandstones, with their accumulated stores of water, underlie an area of about 600,000 square miles. Without the artesian wells, some of which are 4,000 to 5,000 feet deep, much of this vast region would be a barren waste. In this area it is suspected that only part of the water is meteoric. In some of the wells the enormous pressure of the water, the abundance of gases, and the composition of the dissolved constituents all suggest that juvenile sources may also contribute in depth, the pressure being partly due to gases and partly to the weight of overlying rocks.

Many of the *oases* of the Sahara and other deserts owe their existence to the local emergence of artesian water at the surface. Fertilised by the escaping underground water, vegetation flourishes amazingly and makes " a paradise in a setting of blazing sand and glaring rocks." Between the Chad basin and the Sahara the highlands of Erdi and Ennedi constitute an important catchment area. There the occasional rains are readily absorbed by bare sandstones which continue underground far across Libya and Egypt. Many a traveller has died of thirst in the heart of the desert with water only a

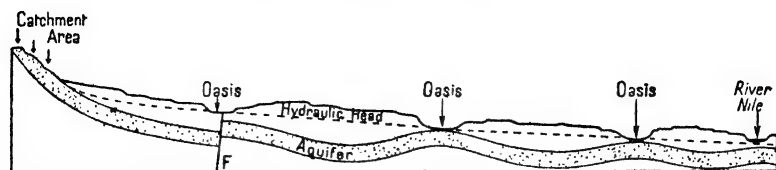



FIG. 58
Idealized section across the Sahara to illustrate conditions favourable to the development of oases

few hundred feet beneath him. Where this usually inaccessible water emerges through fissures or artesian wells, or is brought to the surface by anticlines, or where the desert floor itself has been excavated by the wind down to the level of the ground-water, oases occur (Fig. 58). South of Aswan, the Nile taps part of this artesian water where its channel cuts into an aquifer locally brought up by an anticline.

SWALLOW HOLES AND LIMESTONE CAVERNS

The solution of limestone by rainwater charged with carbon dioxide has already been described (page 116). In limestone districts water readily works its way down through joints and along bedding planes until it reaches an impervious layer, which may be within the limestone formation or beneath it. The water then follows the natural drainage directions until it finds an exit, perhaps many miles away from the intake. Once a through drainage is established, but not until then, dissolved material is carried away and fresh supplies coming in from above continue the work of solution, localised along joints and bedding planes, until a labyrinth of interlacing channels and caves is dissolved out of the limestone (Fig. 55*f*).

The surface openings become gradually enlarged in places where the contours of the ground favour a special concentration of the flow-off, and funnel-shaped holes, known as *swallow holes* or *sink holes* are developed. By continued solution beneath these, and the falling in of loosened joint blocks, the

holes may be enlarged into roughly cylindrical shafts or chasms communicating with great vaulted chambers, perhaps hundreds of feet below (Plate 26A). One of the most impressive of these giant swallow holes in Britain is Gaping Ghyll (Plate 26B), on the south-east slopes of Ingleborough. The shaft goes down for 365 feet into a chamber 480 feet long and 110 feet high. The water escapes through an intricate system of passages into Ingleborough Cave, whence it emerges as the Clapham Beck. In the Ariège (French Pyrenees) two great chasms connected by a long grotto, with a permanent stream from top to bottom, have been explored down to a depth of 1566 feet, and several even deeper examples occur in Italy. The " cavernous limestone " plateau of Kentucky has over 60,000 sink holes and hundreds of caves, including the great Mammoth Cave, which itself has over 30 miles of continuous passages. Another famous American cave, the Carlsbad Cavern of New Mexico, has a " Big Room " nearly 4,000 feet long, with walls over 600 feet apart, and a ceiling rising to a height of 300 feet (Plate 27A).

Occasionally the roof of a cave collapses and leaves another kind of " sink " at the surface. When the roof of a long underground channel falls in, a deep ravine, floored with limestone debris, further diversifies the irregular limestone topography (Fig. 59). Sometimes one part of the roof holds firm, thus forming a natural arch or bridge (Fig. 60). Limestone regions such as those referred to above, having a roughly etched surface, pitted with depressions due to solution or roof collapse, and with underground drainage in place of surface streams, are said to have a karst topography, from the prevalence of these features in the Karst Plateau north-east of the Adriatic coast between Trieste and Cattaro (see Fig. 166).

In addition to the streams which flow through the underground network of passage-ways, there is generally a slow seepage of lime-charged water from innumerable joints and crevices in the roofs and walls of caves. Calcium carbonate is deposited when a hanging drop of such water begins to evaporate or to lose part of its carbon dioxide. When the

[*A. Horner & Sons, Settle*

FIG. 59

Trow Ghyll, on the slopes of Ingleborough, Yorkshire. A dry valley due to collapse of the roof of a former limestone cavern

drop falls on the dry floor of a deserted channel, the remaining calcium carbonate is deposited. Thus, long icicle-like pendants, called *stalactites*, grow downwards from the roof; and thicker columns, distinguished as *stalagmites*, grow upward from the floor (Plate 27). In time stalactites and stalagmites unite into pillars, and these are commonly clustered together in forms resembling organ pipes and other fantastic shapes that are often given fanciful names. Where the water trickles out more or less continuously along a roof joint, a fluted curtain or wavy screen may grow across the cave. When the water comes through a bedding plane it builds up encrustations

[*Am. Mus. Nat. History, N.Y.*

FIG. 60

Natural Bridge, Virginia. Part of the roof of a former limestone cavern

from wall to floor which look like frescoes or " frozen cascades." The internal decoration of caverns in which these varied structures have grown in profusion produces an underground scenery of weird and fascinating beauty.

HOT SPRINGS AND GEYSERS

Ground-water that has circulated to great depths in deeply folded rocks becomes heated, and if a sufficiently rapid ascent to the surface should be locally possible, it will emerge as a

warm spring. Such conditions are rare, however, and really hot springs generally occur in regions of active or geologically recent vulcanism, where they owe their high temperature to superheated steam and associated emanations which rise from subterranean sources and mingle with the meteoric circulation at higher levels. It is probable that some hot springs may be a mixture of meteoric water with hot water expelled from underlying rocks that are undergoing metamorphism.

There are three volcanic regions where hot springs and geysers occur on an imposing scale : Iceland, Yellowstone Park, and the North Island of New Zealand. The waters are highly charged with mineral matter of considerable variety. The Mammoth Hot Springs of Yellowstone Park are rich in calcium carbonate derived from neighbouring limestones. This is deposited at the surface as mounds and terraces of *travertine* (Plate 28A). In all three regions many of the springs are alkaline and carry silica in solution, which is similarly deposited as *siliceous sinter* or *geyserite* (Plate 28B). As to the water itself, investigations show that about 80 to 90 per cent. is ordinary meteoric ground-water. In Iceland, for example, much of it comes from melting snow. However, the minor constituents carried in solution include many unusual elements, a peculiarity which points to a juvenile source and suggests that they must have been swept into the local meteoric water by associated juvenile water or steam. The existence of such steam, however, is not merely a matter of inference. Actual borings through the rhyolite lavas of Yellowstone Park encountered vast quantities of high-pressure superheated steam. In one case the temperature at a depth of 245 feet was found to be 205°C. Moreover, where steam remains uncondensed by admixture with cold ground-water, steam fumaroles discharge at the surface.

Geysers are hot springs from which a column of hot water and steam is explosively discharged at intervals, spouting in some cases to heights of hundreds of feet (Plate 29). The term comes from *Geysir*, the Icelandic name for the Great Geyser, which is the most spectacular member of a group situated in

[Dorien Leigh, Ltd.
(A) Terraces of the Mammoth Hot Springs, Yellowstone National Park

[E.N.A.
(B) White Terraces of Rotomahama, New Zealand. Destroyed by the catastrophic eruption of Tarawera in 1886

HOT SPRING DEPOSITS

[*G. A. Grant, U.S. Geol. Survey*

Geyser in eruption. Old Faithful, Yellowstone National Park

a broad valley north-west of Heckla (Fig. 61). It will serve as a typical example. A mound of geyserite, built up by deposition from the overflowing water, surrounds a circular basin, about 69 feet across and 4 feet deep, filled to the brim with siliceous water at a temperature of 75° to 90° C. From

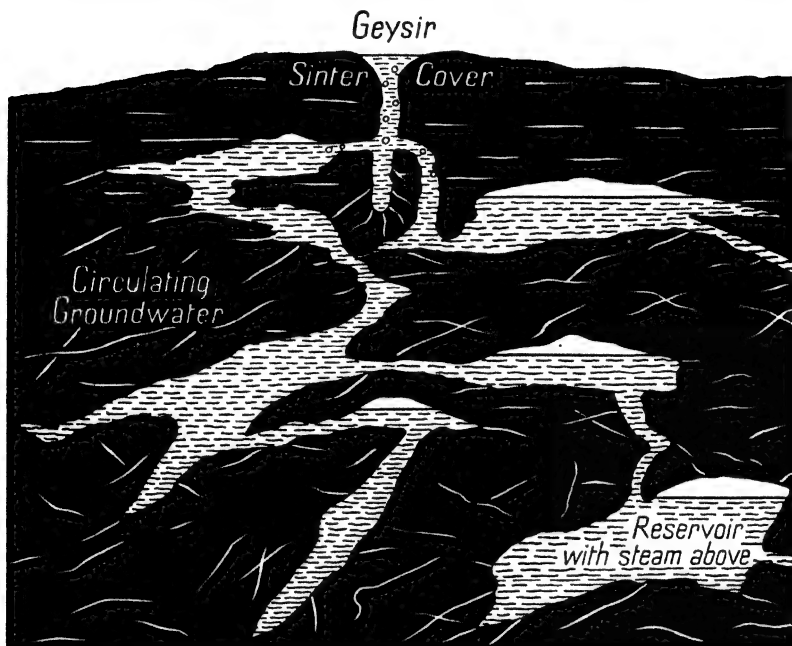



FIG. 61

Schematic section through Geysir (the Great Geyser of Iceland) to illustrate the conditions appropriate to intermittent eruption ; showing subterranean reservoirs fed by ground-waters heated from below by the ascent of superheated steam (*After T. F. W. Barth*)

the middle of the basin a pipe, also lined with geyserite, goes down about 100 feet. At the bottom the temperature of the water is well above that at which the water would boil if it were not for the pressure due to the weight of the water column above it. But the continued accession of superheated steam through cracks in the pipe gradually raises the temperature until eventually the boiling-point is reached far down in the

pipe. A certain amount of water then suddenly expands into steam which heaves up the column and causes an overflow from the basin. This so relieves the pressure on the superheated water in depth that it violently flashes into a vast volume of steam which surges up with irresistible force, hurling the water into the air, sometimes as much as 200 feet.

In some geysers the amount of water discharged is many times greater than that contained in the pipe and basin. In these cases the pipe must therefore communicate with a neighbouring underground chamber into which continuous supplies of both meteoric water and juvenile steam have access. The caves and tunnels which sometimes occur in lava flows would provide the sort of reservoir required. During each period of quiescence the whole system—underground reservoir, communicating channels, pipe, and basin—rapidly fills up and gradually rises in temperature, until the quiet phase of the cycle is terminated by the paroxysm of high-pressure boiling which brings about a roaring eruption of water and steam.

Deposition from Ground-waters

As indicated by the discussion on pages 116-18, the chief ingredients carried in solution by ground-water are the bicarbonates of calcium, magnesium and iron, and colloidal silica. Examples of deposition of calcium carbonate as stalactite and stalagmite in limestone caverns, and as travertine from the waters of hot springs, and of silica as siliceous sinter or geyserite, also from the waters of hot springs, have already been mentioned. These cases are easy to understand, as they are clearly due to evaporation, loss of carbon dioxide, or cooling. The return of dissolved material to the rocks through which ground-water is circulating involves the operation of much more complex and delicately balanced processes which are still but little understood. Precipitation may be brought about by such factors as loss of gases and consequent decrease of solvent power ; cooling while waters are ascending ; changes of pressure during circulation ; or the mingling of waters from

different sources. Moreover, as a result of reaction between solutions and the materials through which they pass, one substance may be precipitated and another taken into solution. Only brief notes on some of the chief results of deposition from ground-water can be given here.

Cementation of porous sediments occurs when deposition takes place between the particles of the rock. Loose sands may thus become calcareous, siliceous, or ferruginous sandstones, according to the nature of the cement introduced between the grains.

Replacement, or substitution of one substance for another, is well exemplified by parts of certain limestone formations in which calcite has been replaced by dolomite or chalybite or silica. The change often takes place atom by atom, so that the original structures are perfectly retained. Calcareous fossil shells may thus be transformed to any of the materials mentioned, as well as to others, less common, with complete preservation of the original form and of the most intricate structural details. Even organic matter can be replaced in this way. Water-logged tree trunks buried in sand, or stumps of trees overwhelmed by volcanic ash, may thus be petrified. Such fossil wood, with all the tissues perfectly reproduced in opaline silica or calcite, is notably abundant in Yellowstone Park, and in parts of Burma and Queensland.

Nodules and *concretions* form in sediments by concentrated cementation or replacement, where deposition is localised around a nucleus of some particular mineral grain or fossil which initiates the precipitation. Their composition is generally widely different from that of the formation as a whole. *Flint*, for example, is a concretionary form of silica occurring in the Chalk as scattered nodules of irregular shapes and also as tabular sheets and vertical stringers (see Fig. 151). Groundwater percolating through the Chalk at some stage after its uplift from the sea floor picked up colloidal silica from minute and easily dissolved opaline sponge spicules dispersed through the formation. By replacement of calcium carbonate, wherever conditions were favourable, the silica was then deposited as flint which, being insoluble, was not again redissolved.

Similar deposits of silica occurring in other limestones are usually referred to as *chert*. Calcareous and ferruginous nodules, characteristically of ellipsoidal shapes, are common in some of the clays and shales of the Jurassic and Carboniferous systems in Britain.

Small *veins* of common minerals, such as calcite and quartz, may be formed from ground-waters in joints and fault fissures, or in gashes across the limbs of folds. In tightly folded rocks and in areas of regional metamorphism, irregular quartz veins are locally very abundant. Many of these have been deposited in tension clefts from siliceous water "sweated out" of the original rocks during orogenesis. Most *mineral veins*, however, and especially those containing commercially valuable ores, have been deposited from hydrothermal solutions of juvenile origin, generally in association with the expiring igneous activity of the period concerned.

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[*Aircraft Operating Co. of Africa*

Aerial view across the Hex River Valley and Mountains, Cape Province, South Africa

[*F. N. Ashcroft*

Valley widening by rapid weathering. Tobel Drun ravine, near Sedrun, Switzerland. Flat-surfaced deposits in front mark the site of a former lake

Chapter X

RIVER ACTION AND VALLEY DEVELOPMENT

Some General Considerations

The necessary conditions for the initiation of a river are an adequate supply of water and a slope down which to flow. As we have already seen, Perrault was the first to discover that an adequate supply is provided by the rainfall. From the result of his pioneer work in the valley of the upper Seine he justly concluded that " rain and snow waters are sufficient to make Fountains and Rivers run perpetually." Rivers are partly fed from ground-waters, and some have their source in the melt-waters from glaciers, but in both cases the water is derived from the meteoric precipitation. In periods of drought rivers may be kept flowing, though on a diminished scale, entirely by supplies from springs and the zone of intermittent saturation. When these supplies also fail, through the lowering of the water table, as commonly happens in semi-arid regions, rivers dwindle away altogether. However, even then water may still be found not far below the surface where the floors of such intermittent streams have a covering of alluvium.

The initial slopes down which rivers first begin to flow are provided by earth movements or, more locally, by volcanic accumulations. Many of the great rivers of the world, *e.g.* the Amazon, Mississippi, and Congo, flow through widespread downwarps of the crust which endowed them with vast ready-made drainage basins from the start. The majority of rivers, however, originated on the sides of uplifted regions where, often in active competition with their neighbours, they gradually evolved their own drainage areas.

Most rivers drain directly into the sea. But in areas of internal drainage permanent or intermittent streams terminate in lakes or swamps having an area such that evaporation just balances the inflow, the conditions being such that the water is

unable to accumulate to the level at which it could find an outlet. Notable examples occur in Central Asia and Australia.

The development of a river valley depends on the original surface slope ; on the climate, which determines the rainfall ; and on the underlying geological structure, which determines the varied resistance to erosion offered by the rocks encountered. Where a newly emergent land provides an initial seaward slope, the rivers which flow down the slope, and the valleys which they excavate, are said to be *consequent.* The valley sides constitute secondary slopes down which tributaries can develop ; these streams and their valleys are distinguished as *subsequent.* Later, of course, other generations of tributaries are added. A main river and all its tributaries constitute a river system, and the whole area from which the system derives water and rock-waste is its basin. Weathering continuously supplies rock-waste, which falls or is washed by rain into the nearest stream. The latter carries away the debris contributed to it, and at the same time acquires still more by eroding its own channel. Valleys develop by the removal of material, all of which is carried away by the streams which drain them. The load acquired by the main river is ultimately transported out of the basin altogether or deposited in its lower reaches. Deposits are, of course, dropped on the way at innumerable places, but these are only temporary halts in the journey towards the sea. Rivers are by far the chief agents concerned in the excavation of valleys, not merely because of their own erosive work, but above all because of their enormous powers of transportation.

The excavation of valleys in turn involves the development of residual landforms (Plate 30), such as peaks, hills, ridges, and isolated pinnacles of resistant rocks (Fig. 62). The original uplifted area is thus gradually dissected into a varied and slowly changing landscape. Sooner or later, as rock-waste continues to stream away from every part of the area in turn, valleys are widened and the intervening divides are reduced, until the region may be worn down to a low-lying surface of faint relief which is called a *peneplain* (almost a plain). The whole sequence of changes passed through during this long

Fig. 62
A Dartmoor tor at the summit of a residual hill; carved from well-jointed granite by rain and wind. Bowerman's Nose, Manaton, Devonshire

evolution is called a *cycle of erosion.* It is convenient to divide the cycle into three successive stages which, by analogy with a lifetime, are referred to as youth, maturity, and old age. Each stage is characterised by distinctive types of landforms. In this chapter we shall be mainly concerned with the cycle of erosion in humid regions, where the work of rain and rivers is in control. In other climatic regions, such as deserts, where the work of the wind is chiefly in evidence, and frigid regions, where glaciers and ice-sheets are the supreme agents, the corresponding cycles of erosion involve the development of landforms which are very different from each other and from those of humid regions. The cycle of river erosion does not always run its course without interruptions. Further uplift may take place while a cycle is still uncompleted, or the area may be glaciated. For both reasons many of our British rivers are still in their infancy, and the landscapes associated with them are partly inheritances from glacial and pre-glacial times.

Nevertheless, the valleys of the present day, whether in Britain or elsewhere, provide representatives of all the stages in the cycles of erosion now in progress. We are thus enabled to study by direct observation how they gradually develop. We shall have to consider in turn how the lands are eroded and the rivers acquire their load of rock-waste ; how the rivers themselves erode their channels and transport and deposit their load ; how valleys are lengthened, deepened, and widened ; how river systems develop in plan and compete with their neighbours in the struggle for space ; how topography varies according to the stage reached in the cycle of erosion ; and how it is further varied by interruptions of the normal cycle.

RAIN EROSION

The chief mechanical effect of rain as it pelts down on the mantle of surface materials is to wash loose particles to lower levels. Eventually the rain-wash is swept into rills and streams. During a sudden cloudburst a sheet of flowing water may be locally produced which undercuts and removes the turf on sloping ground, sweeping the underlying soil to the foot of the slope, and leaving a long gash in the hillside. The gash is gradually deepened into a gully by recurrent rains, and as soon as the water table is tapped it begins to carry water and becomes a rivulet. This is one of the ways in which tributaries originate.

In semi-arid regions, where the occasional rains are often exceptionally violent, rain-gashing reaches spectacular proportions in sloping ground underlain by clay or soft earthy deposits. Such land is sculptured into an intricate pattern of gullies and small ravines, separated by sharp spurs and buttresses. The gullies grow backwards into the adjoining upland, and the intervening ridges in turn are further cut up into smaller ribs and trenches (Plate 32A). Tracts of the almost impassable country so developed are graphically described as *badlands* in North America, where they are widely scattered from Alberta to Arizona (Plate 32B).

The curious structures known as *earth-pillars* develop locally from spurs left on the slopes of valleys carved in boulder clay (Plate 33A). Wherever a boulder is encountered while the surface is being worn down by rain erosion, it acts like an umbrella over the underlying clay. Where the slope is sheltered from strong winds, earth-pillars of surprising height, each surmounted by a protective cap, may then be etched out by the rain. Some of the pillars of Botzen in the Tyrol reach a height of 69 feet, and smaller examples occur in favourable situations in Scotland and other regions where boulder clay and easily eroded conglomerates (Plate 33B) are exposed to the weather.

Soil-creep and Landslides

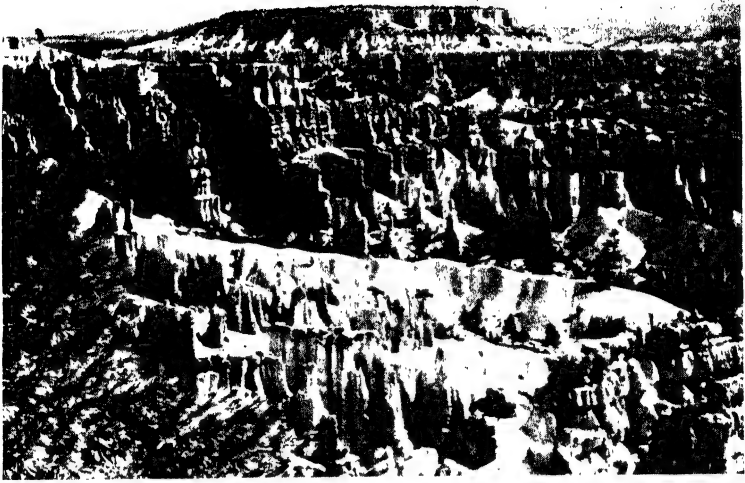
Between the extremes of rain-wash on gentle slopes and rock-falls from precipices there are various kinds of mass movements of surface materials downslope, which result from the action in different combinations of water, frost, organisms, and gravity. All these processes co-operate with weathering in widening valleys (Plate 31).

Slow downward movement of soil on hillsides, known as *soil-creep*, is evidenced by tilted fences, bulging walls, and the outward curving of tree trunks near the ground. Interstitial rain-washing, together with various less obvious processes, all co-operate. Ice crystals heave up stones and particles of all sizes during frost. The outward heave and the subsequent drop when thaw sets in are both in a downhill direction. Imperceptible movements due to expansion and contraction, or to the wedging action of rootlets, take place under the control of gravity, so that the cumulative effect is downwards. Even the sub-soil and the upper parts of the bedrock share in this movement. The upper ends of steeply dipping or cleaved beds are prised apart by frost and rootlets until they gradually curve over in the downhill direction. This results in apparent dips which, exposed in cuttings and gullies, may depart considerably from those of the undisturbed formation.

When soil becomes thoroughly water-logged, as happens

particularly in colder climates and at high altitudes after the melting of snow, the downward creep passes into actual flow and is then described as *solifluction* (soil-flow). Flows of mud and peat, referred to as bog-bursts, occur periodically in Ireland.

The same group of processes operating in screes leads to similar results. Moreover, screes become bodily unstable as fragments fed from above gradually steepen the slopes. After a thorough soaking and lubrication by water from rain or melting snow, the weight is increased, while friction and the angle of repose (normally 25°–35°) are decreased. The scree thereupon begins to slide. In the gorges of rivers in the Himalayas and other ranges of vigorous relief such *debris-slides* or *rock-avalanches* sometimes occur on a gigantic scale. The valley below may be dammed across. A lake then forms on the upstream side and, bursting suddenly through the wall of debris, may cause a disastrous flood. In sub-arctic regions, where frost and thaw are especially active, *rock-glaciers* or *stone-rivers* spread outwards on suitable slopes. The mechanisms of these phenomena are intermediate between these responsible for soil-creep and debris-slides.

It is a matter of common observation that steep grassy slopes above valley floors are often scored at intervals with little *terracettes* or " sheep-tracks " in the soil, particularly where the stream undercuts and steepens the banks. These features are due to small landslips which, as they are of frequent occurrence, contribute largely to the removal of mantle deposits. The essential conditions are lack of support in front and lubrication behind. Similar conditions favour *landslides* on a bigger scale, wherever slumping (Fig. 63) or sliding (Fig. 64) can occur on the sides of undercut slopes, precipices, and cliffs, or of road, railway, and canal cuttings, particularly where heavy massive rocks (*e.g.* plateau basalt) overlie weak and easily lubricated formations. Slumping takes place on a curved slip plane, and a backward tilting of the surface often results. Sliding occurs when bedding and cleavage planes, fault fractures, or joints dip towards a valley or other depression at a dangerous angle.

[*Am. Mus. Nat. History, N.Y.*

(A) Fretted erosion of well bedded and jointed strata at the head of Bryce Canyon, Utah

[*N. H. Darton, U.S. Geol. Survey*

(B) The Big Badlands of South Dakota

[G. P. Abraham, Ltd., Keswick

(A) Buttress of boulder clay developing into earth pillars, Val d'Hérens (tributary of Upper Rhône)

H.M. Geol. Survey

(B) Earth pillar of soft conglomerate (Old Red Sandstone), Aultderg Burn, south of Fochabers, Elgin

PLATE 34

[*F. N. Ashcroft*

Landslide (1927) from the Motto d'Arbino across the Valle d'Arbedo, near Bellinzona, Ticino Valley above L. Maggiore

[H.M. Geol. Survey

(A) The "tools" of a river, left stranded in dry weather. Valley cut in boulder clay, Anglezark Moor, east of Chorley, Lancashire

[R. Welch

(B) Pot-hole drilled in Tertiary basalt, Glenariff, Co. Antrim

Plate 34 illustrates a landslide (as seen in 1935) that obstructed a tributary of the Ticino valley in 1927. Several years previously a crack that appeared near the top of a hill

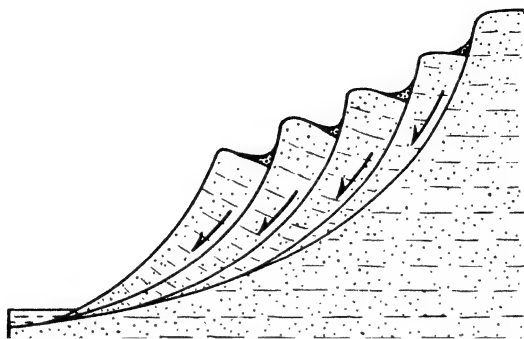



Fig. 63
To illustrate slumping on curved surfaces in unconsolidated or other weak formations ; showing characteristic back-tilting at the surface

on the right-hand side had slowly developed into a gaping fissure about 6 feet wide. Subsequent movements were carefully measured by setting up a line of stakes and recording

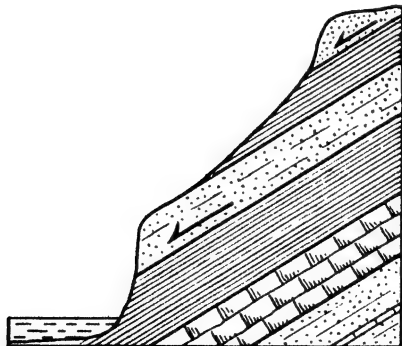



Fig. 64
To illustrate conditions favouring rock slides on lubricated bedding planes

their positions several times daily. One day in 1927 a sudden movement of 8 or 10 feet occurred. A warning was immediately telephoned, and the danger zone was evacuated.

Forty-eight hours later the long-threatened slide took place, fortunately without loss of life.

The sediments of the flat terrace seen in the foreground of Plate 31 were deposited in a lake that formerly occupied a long stretch of the Upper Rhine and its tributaries. The lake was impounded by a gigantic prehistoric landslide that blocked the main valley near Flims, about 30 miles downstream. The landslide debris itself covers an area of some 20 square miles, and formed a dam (since cut through by the river) not less than 2,700 feet thick.

Erosion and Transport by Rivers

The work of river erosion is accomplished in four different ways, all of which actively co-operate.

(*a*) *Corrosion* is the solvent and chemical action of the water of the stream on the materials with which it comes into contact.

(*b*) *Hydraulic action* is the mechanical loosening and removal of materials by water alone. Flowing water can sweep away loose deposits and wash out particles from weakly resistant sediment. A river may not acquire much new material by sluicing its channel, but the coarser part of the load is likely to be dropped over and over again during transit (Plate 35A), and each time it has to be picked up afresh before transport can proceed. Where the current is strong enough, as when a river is in spate, water may be driven under jointed slabs with sufficient force to hoist them up, turn them over, and so make them available for transport.

(*c*) *Corrasion* is the wearing away of the sides and floor with the aid of the boulders, pebbles, sand, and silt which are being transported. By scour and impact even the hardest bedrocks are excavated and smoothed. The drilling of *pot-holes* is one of the most potent methods of down-cutting. These develop in the depressions of rocky channels or from hollows formed where boulders and pebbles, acting like drilling tools, are rapidly swirled round by eddies (Plate 35B). Vertical holes are cut deeply into the rock as the water plunges in and keeps the drilling tools in action by its spiral motion. As the boulders

wear away, and are swept out with the finer materials, new ones take their place and carry on the work. In front of a waterfall very large pot-holes may develop in the floor of the "plunge-pool." This leads to deepening of the channel, and at the same time a combination of hydraulic action and corrasion undermines the ledge of the fall. The eddying spray behind the fall itself is particularly effective in scouring out the less resistant formations that underlie the ledge (Fig. 68). Blocks of the ledge are then left unsupported and fall away at intervals, thus causing a migration of the fall in an upstream direction, and leaving a gorge in front.

(*d*) *Attrition* is the wear and tear suffered by the transported materials themselves, whereby they are broken down, smoothed, and rounded. The smaller fragments and the finer particles liberated as by-products are then more easily carried away.

The solid part of the load carried by a river includes the rock-waste supplied to it by rain-wash, surface creep and slump, etc., and by tributaries and external agents such as glaciers and the wind, together with that acquired by its own destructive work, as described above. The debris is transported in various ways. The smaller particles are carried with the stream in suspension, the tendency to settle being counterbalanced by eddies. Larger particles, which settle at intervals and are then swirled up again, skip along in a series of jumps. Pebbles and boulders roll or slide along the bottom, according to their shapes. Very large blocks may move along on a layer of cobbles which act like ball-bearings.

The transporting power of a stream rises very rapidly as the velocity increases. Experiments show that with debris of mixed shapes and sizes the load that can be carried by running water is proportional to something between the third and fourth power of the velocity. But for fragments of a given shape, the largest size that can be moved is proportional to the sixth power of the velocity. Very large boulders which may remain stationary in the stream bed for long periods can thus be carried downstream by intermittent storm waters.

If the supply of debris exceeds the load that can be transported, or if the velocity is checked, part of the material is left

behind or deposited on the river bed, to be picked up later when the stream is running more vigorously. Each time, the largest ingredients of the load are the first to be dropped and the finest are the first to be moved on again. In consequence, a river begins to sort out its burden as soon as it receives it. From source to mouth the deposited materials gradually change in type from coarse to fine.

In addition to their solid load, rivers transport a great deal of material in solution, most of which is contributed to them by surface and underground drainage waters. The proportions of dissolved and solid load vary enormously from place to place and from time to time. Data referring to the work of erosion and transport achieved by all the chief rivers of the world over representative periods of years show that on an average about 8,000 million tons of rock-waste are removed from the lands and transferred to the sea every year. Of this total about 30 per cent. is carried in solution. The drainage areas are at present being worn down at an average rate of one foot in about 9,000 years, but the average rates for individual regions range from a foot in 400 years for the Irrawaddy basin to a foot in 47,000 years for the low-lying basins draining into Hudson Bay.

Lengthening and Deepening of Valleys

In the upper part of a typical stream gradients are steep, the water runs swiftly and the narrow valley is either a gorge or V-shaped, and the walls are often rocky. This is the *torrent* or *mountain tract*. Lower down, in the middle part of the stream —the *valley tract*—slopes are gentler and the valley has become much wider. Nearer the sea, in the *plain tract*, the valley includes a broad flood-plain, which is liable to deposition whenever the river overflows its banks. Seawards, the river may flow into an estuary, or the plain tract may grow outwards as a delta.

Not all rivers, however, have yet had time to develop a full sequence of tracts. Some streams pass directly from the valley tract into the sea ; others, much younger in develop-

[*F. N. Ashcroft*

Via Mala Gorge, looking upstream between Thusis and Zillis, Switzerland

[*G. P. Abraham, Ltd., Keswick*

(A) Infilling of a lake by sediment. Head of Derwentwater viewed from the Watendlath path, Lake District

[*G. P. Abraham, Ltd., Keswick*

(B) Alluvial flats marking the site of a former lake. Borrowdale, looking north from Glaramara. Derwentwater and Skiddaw in the background

ment, may still be entirely in the torrent stage. Such conditions are also brought about when submergence of the land takes place, and the lower reaches of the rivers already developed are " drowned."

In general, young valleys are lengthened and grow backwards into the land by *headward erosion*, due to rain-wash, gullying, and the creep and slump of surface materials at their heads. The torrent tract thus extends inland. At the same time the valley is deepened by the active co-operation of all the processes of river erosion. When the valley floor is cut down so rapidly that there has been insufficient time for any appreciable widening of the sides, a vertical chasm with precipitous walls results. The well-known Lütschine and Via Mala gorges of Switzerland are familiar examples (Plate 36). The cutting of gorges is favoured in areas well above sea level where the rocks are highly resistant to weathering and the widening processes (page 160) act slowly. Waterfalls often have gorges in front of them, formed during the cutting back of the rock face over which the water plunges. The more spectacular gorges, like those of the Himalayas and Andes, are cut by extremely active rivers which have continued to saw downwards through the rocks during the actual uplift of the mountain ranges.

Where widening and deepening proceed together, as happens more commonly (and in any case as the widening processes catch up), V-shaped valleys are developed, and the V gradually opens out as time goes on. The torrent tract thus evolves into the valley tract, and each gradually migrates inland as the source continues to recede by headward erosion.

Grading of Rivers

Since a river which flows into the sea must have a gradient towards the sea, the deepening of a valley is necessarily limited by sea level. An imaginary extension of sea level under the land is called the *base-level* of river erosion. The profile of a river along its length from mouth to source is therefore a line

which is tangential to sea level and rises inland. In youth the profile is more or less irregular, but as maturity is attained the major irregularities are smoothed out. It is easy to see how the initial irregularities are destined to disappear. At each point of the profile there must be a certain minimum gradient which will give the stream just sufficient velocity to carry off the load which it acquires. Wherever the gradient is steeper than the minimum there necessary, the increased velocity so brought about promotes erosion which wears the gradient down. Wherever the gradient is less steep, the velocity is checked, and the resulting deposition of part of the load builds the gradient up.

When the profile is developed so that it everywhere provides the necessary minimum gradient, it is called a *graded*

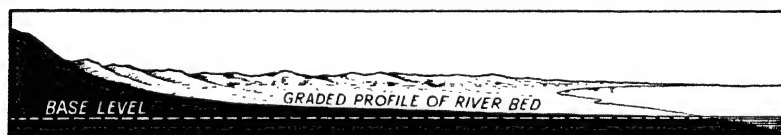



FIG. 65

To show the relation between base-level and grade

(*After R. S. Tarr and O. D. von Engeln*)

profile or a *profile of equilibrium.* Since this gradient varies with the stream-flow, being least when the stream-flow is greatest, it follows that it is steepest towards the source. Under ideal conditions it would theoretically have the shape of a hyperbolic curve, concave upwards (Fig. 65). The ideal curve is never quite attained, however, because it implies a delicate balance between gradient on the one hand, and stream flow, transporting power, and load to be carried, on the other ; a balance which is never maintained for long. Variations in the supply of water and rock-waste from time to time, and especially where tributaries come in, inevitably involve slight and temporary fluctuations. A river or any of its reaches in which the profile of equilibrium is thus approximately established is itself said to be *graded* or *at grade.*

Downward erosion does not cease when a river is graded, though it may then become very slow. For a given stream-

flow, the necessary gradient decreases as the load decreases. And as the whole relief of the drainage area continues to be reduced, the load itself systematically decreases as time goes on, while the stream-flow remains about the same. Consequently the graded profile can be, and is, slowly flattened out. Base-level, always being approached but never quite attained, is its only limit.

The level of the main river at the point where a tributary enters acts as a *local base-level* for that tributary. In the normal development of a river system graded tributaries thus become so adjusted to the main stream that they join it tangentially. When tributaries fail to behave in this way the absence of adjustment is a clear indication that the cycle of erosion has been interrupted by changes of slope due, as a rule, to earth

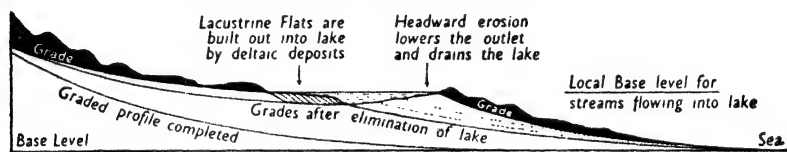



FIG. 66

To illustrate the elimination of a lake by sedimentation at the inlets and headward erosion at the outlet. Successive positions of graded profiles are shown before and after elimination

movements or glaciation. The alluvial fans and cones described on page 201, and the waterfalls of recently glaciated countries (page 221), are conspicuous features resulting from such interruptions.

Various irregularities in a river channel may postpone the general establishment of grade, though above and below these features individual reaches of the river may be temporarily graded. A lake, for example, acts as a *local base-level* for the streams discharging into it. Lakes that occupy deep depressions have a very long life, but shallow ones are, geologically speaking, soon eliminated. A lake is a trap for sediments, destined to be silted up by deltaic outgrowths from the inlets. At the same time down-cutting of the outlet lowers the level, drains the lake, and reduces its area (Fig. 66). Ultimately the lake is replaced by a broad lacustrine flat through which the

river flows (Plate 31). Down-cutting through the sediments and underlying rock-floor then proceeds until continuity of grade is established between the upper and lower reaches of the river. In the Lake District (page 183) lakes can be seen in every stage of elimination, together with lacustrine flats in which young valleys are already being developed (Plate 37).

A resistant formation encountered by a river also retards the establishment of grade and acts as a temporary base-level for the stream above until it is cut through by waterfalls and rapids. The latter persist so long as the outcrop of obstructive rock remains out of grade with the graded reaches in the softer rocks exposed above and below.

Waterfalls

Where an outcrop of resistant rock is followed downstream by a weaker formation, the latter is relatively quickly worn down. At the junction, and subsequently above it, the river-bed is steepened and the stream rushes down the slope as a

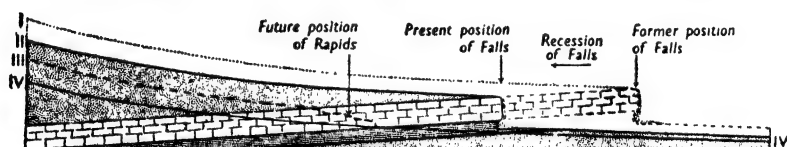



Fig. 67

Successive stages in the recession and elimination of a waterfall

I Profile of stream (drawn as graded) above an early position of the falls
II Present profile above falls
III Future profile after degeneration of the falls into rapids
IV Future profile (graded throughout) after elimination of falls and rapids

rapid. If the face of the resistant rock becomes vertical, the stream plunges over the crest as a *waterfall.* The processes which bring about recession and gorge development have already been described. Waterfalls eventually degenerate into rapids as the profile begins to approach grade (Fig. 67). A fall that descends in a series of leaps is sometimes referred to as a *cascade.* An exceptional volume of water is implied by the term *cataract,* which may be applied either to waterfalls or,

more commonly, to steep rapids. Rapids are favoured throughout the wearing down of an obstructive formation if its dip is steep. And where the dip is downstream, even if it be moderate, the development of a vertical face is precluded, and rapids are formed instead of a waterfall.

Where a bed of strong rock, horizontal or gently inclined,

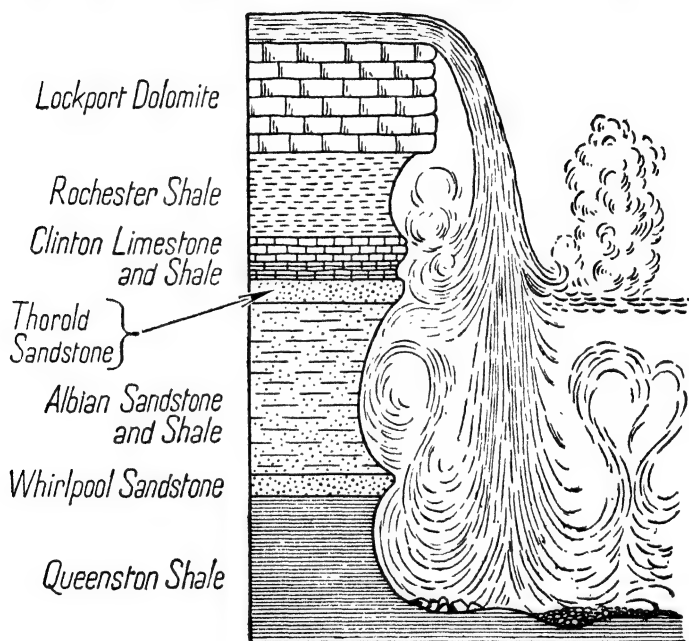



FIG. 68
Section across the Niagara Falls showing the sequence of hard and soft formations and illustrating the mechanism of recession

overlies weaker beds the former is the " fall-maker," and scouring of the softer beds underneath leads to undermining and recession. At High Force in Teesdale the tough and well-jointed Whin Sill is the fall-maker. In the Yorkshire dales falls are commonly developed over ledges of limestone underlain by shale.

The *Niagara Falls* are the classic example of this type (Plate 38). As shown in Fig. 68 the river plunges 160–170

feet (according to the depth of the river below) over a thick ledge of limestone. The American Falls (frontage, 1,060 feet) are separated from the Canadian or Horseshoe Falls (frontage, 2,800 feet) by Goat Island. The mean flow, before the diversion of much of the water to hydro-electric plants, was eighty-five times that of the Thames. Most of the water passes over the Horseshoe Falls which, as their name implies, are receding much more rapidly (3–4 feet a year) than the American Falls (a few inches only). After the withdrawal of the Labrador ice sheet from this region about 20,000 years ago (page 243), the Niagara River followed a course towards Lake Ontario, which led it over a pre-glacial escarpment. The fall thus initiated has since receded 7 miles, leaving a gorge of which the rim is about 200 feet above the river, and on the average about 360 feet above the river floor. Ultimately the Falls will cut back until Lake Erie is partly drained.

The *Kaieteur Falls* on the Potaro River in British Guiana are also of this type, though in this case the ledge, over which the river makes a sheer leap of 740 feet, consists of hard conglomerate, and is underlain by softer sandstones and shales.

The *Yellowstone Falls* (Upper, 109 feet ; and Lower, 308 feet) are cutting through an immensely thick mass of rhyolite, parts of which have been altered and weakened, and at the same time gorgeously coloured, by chemical changes due to thermal waters. Hot springs still emerge along the floor of the canyon, which in places is 2,500 feet deep. The fresh resistant layers of rhyolite are the fall-makers. Rugged spurs and pinnacles are left as the walls of the canyon are worn back, all vividly splashed with colours of every hue (Plate 39A).

Uplifted areas of plateau basalts of varying resistance provide the structural background for some of the world's greatest falls. In the British Isles the most attractive examples of this kind are those of Glenariff in Antrim. At the *Victoria Falls* (Plate 39B) the Zambesi drops 360 feet from a nearly level basaltic plateau into a gorge 60 miles long, through which it rushes as a powerful torrent with surging rapids at intervals. The extraordinarily acute swerves of the upper

part of the gorge well illustrate the dependence of form on structure. Shatter zones which lie athwart the general course of the river, and furnish easily removable masses of basalt, have controlled the zigzag course picked out by the falls and followed during their recession.

The *Guayra Falls* of the Paraná River, where it becomes the boundary between Brazil and Paraguay, have developed in the Paraná basalts. Here a narrow gorge has been cut deeply back into the broad river floor, so that, besides the fall at the head, there are twelve lateral falls on one side of the gorge and five on the other. Taken as a whole this three-mile panorama of falls is the greatest in the world. Although the height is only 130 feet, the mean flow of water is more than twice that of Niagara, rising to six times greater when the river is in flood. Tributaries entering the Paraná below Guayra also descend in falls, the chief example being the *Iguazu Falls* on the Brazil-Argentine boundary. These are twice as high as the Guayra Falls, but, except in flood, the volume is much less than that of Niagara.

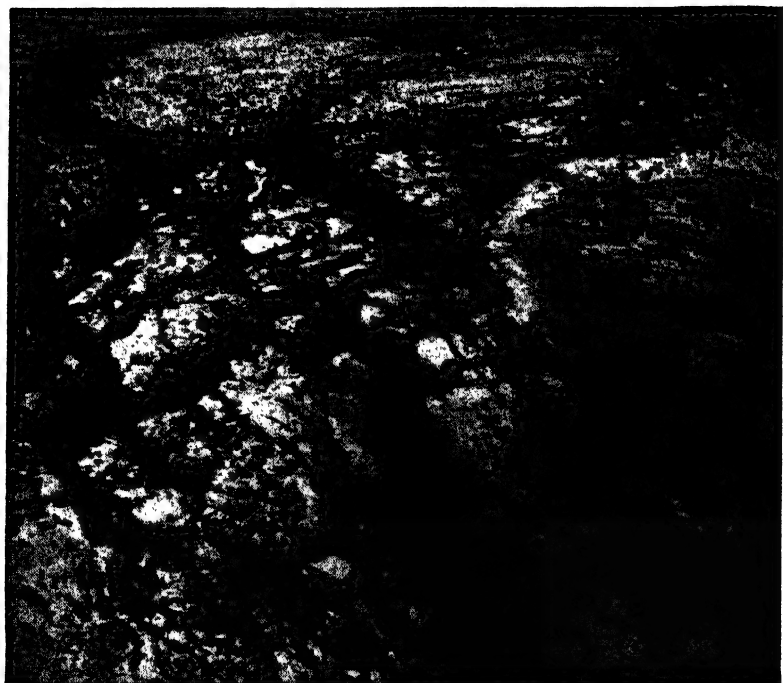
Where rivers pass from uplifted areas of metamorphic and massive igneous rocks to a plain of weakly resistant formations, waterfalls are initiated and often gain height as they recede. The rivers flowing from the hard rocks of the Appalachian uplands have thus developed falls and rapids along the " fall-zone " before they reach the softer sediments of the Atlantic coastal plain. More spectacular examples of this type are the *Paulo Affonso Falls* of the Rio Francisco in the Pre-Cambrian crystalline rocks of N.E. Brazil, with a drop of 270 feet at the head of a canyon 42 miles long ; the *Aughrabies Falls* (460 feet), where the Orange River passes into a grim and desolate gorge of naked granite and gneiss (Fig. 69) ; the *Grand Falls of Labrador*, remarkable for a steeply slanting crest which gives the River Hamilton a high velocity even before it begins its leap of 300 feet ; and the *Gersoppa Falls* in the Western Ghats of N.W. Mysore, which have a sheer drop of 830 feet. In the monsoon floods the last of these has some claim to be considered the greatest single fall in the world, for it then combines great height with exceptional volume. In the dry season, however,

[*South African Air Force*

FIG. 69

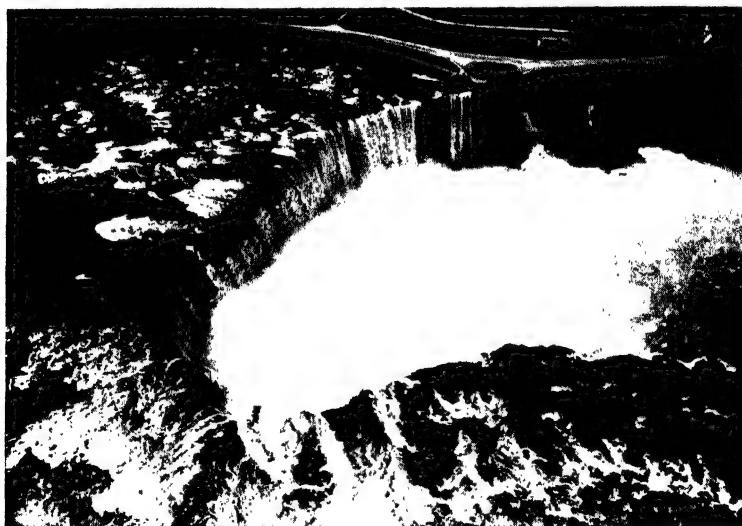
Aerial view of the Aughrabies Falls and Gorge, Orange River, South Africa

it dwindles to a trifling flow. There are many falls of greater height, but these are all due to small streams falling over precipices already provided for them (see Plate 53).

WIDENING OF VALLEYS

Widening of valleys by the wearing back of the sides is accomplished by a great variety of processes. These include the scouring and steepening of the channel sides by the river itself; rain-wash and gullying; soil-creep, slumping, land-slides, and avalanches; chemical weathering and leaching by ground-waters; removal of loose material by wind; and the general co-operation of incoming tributaries, which widen the

[*Hamilton Maxwell Inc., N.Y.*

(A) The American Falls. Goat Island on right

[*Hamilton Maxwell Inc., N.Y.*

(B) The Canadian or Horseshoe Falls

NIAGARA FALLS

[*T. L. Bierwert, Am. Mus. Nat. History, N.Y.*

(A) The Great Falls of the Yellowstone, Wyoming

[*E.N.A.*

(B) Victoria Falls, Southern Rhodesia

main valley where they enter it. The V-shaped cross-profile, which is characteristic of valleys widened in homogeneous rocks, opens out more quickly in soft rocks than in hard, and this effect controls the form of the profile at all levels. Thus, in a valley carved through a series of alternating hard and soft beds the sides rise by slopes which are steep and precipitous where the edge of a hard band outcrops ; terraced, across the exposed top of such a band ; and of intermediate gradient where the rocks are less resistant. The Grand Canyon of Colorado clearly illustrates—at a very youthful stage—this dependence of profile on structure (Fig. 70). At the other extreme, valleys in broad structural downwarps at a low level

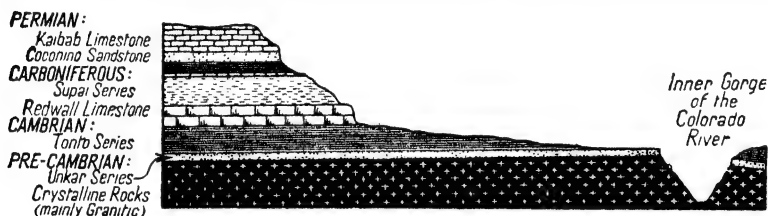



FIG. 70

Section across the south wall of the Grand Canyon of the Colorado at Grand Canyon Station, Arizona. Scale (horizontal and vertical) 1 inch = 1 mile. (*After Darton*) See also Plate 1 and Fig. 103

are wide and have all the superficial characteristics of old age from the start.

Young streams are rarely straight for any distance, but tend to follow a winding course (Fig. 71), determined in the first instance by variations in the rocks encountered and in the structures of those rocks. Several effects of fundamental importance are brought about as water flows round a curve. The main current of the stream (AB in Fig. 72) is deflected towards the outer bank well beyond the beginning of the curve. At the same time the centrifugal force acting on the water concentrates it towards the outer bank where it heaps up. A return current along the bottom (*a*, *b*, *c*, *d*, in Fig. 72), directed towards the inner bank, is thus set up. The stream flows, in fact, with a screw-like motion. These conditions obviously involve maximum erosion on the outside of the curve and

[*H.M. Geol. Survey*

Fig. 71

Youthful valley with overlapping spurs. Crossdale Beck, Ennerdale, Cumberland

minimum erosion or deposition on the inside (Fig. 73). The resulting changes in the river channel and valley may be summarised in order, as follows (Fig. 74) :

1. The channel is deepened on the outer side of each bend.

2. The outer bank is worn back and undercut by lateral erosion, and the slopes above are consequently steepened, locally into river cliffs.

3. As each bend is thus widened and deepened laterally, the river shifts towards the undercut slope, and a tapering spur, sometimes called the "slip-off slope" is left on the

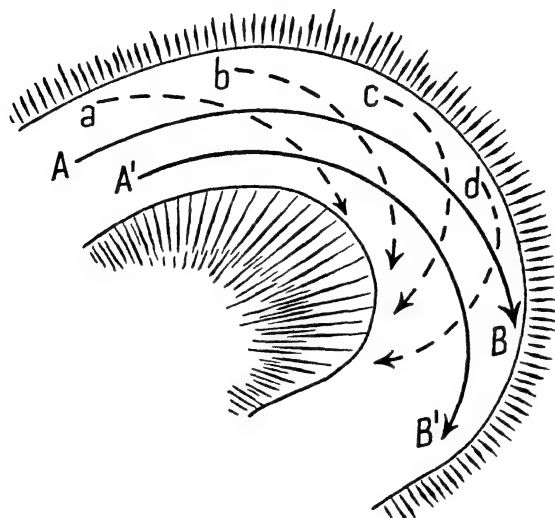



Fig. 72
To illustrate the flow of a river round a bend (in plan)

opposite side, often with a shingle- or sand-bank at its foot, deposited there by the bottom current (Plate 40A; see also Plate 41A). The valley thus becomes highly asymmetrical

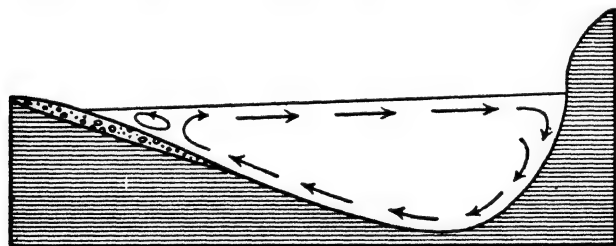



Fig. 73
To illustrate the flow of water round a bend (in section) and the resulting lateral corrasion and deposition

in cross-profile. In plan, the interlocking spurs alternate with the undercut slopes.

4. Each bend is enlarged downstream as well as laterally, and thus tends to migrate downstream as a whole. As each of the migrating bends of a sinuous stream reaches the spur next

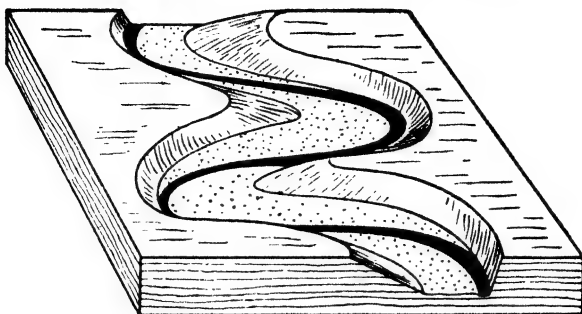



FIG. 74

Widening of a valley flow by lateral erosion and downward migration of bends. The swinging stream eventually trims each overlapping spur into a bluff, leaving a "slip-off" slope on the other side

below, the latter in turn is undercut and trimmed off, while deposition now begins at the foot of the temporarily abandoned undercut slope on the other side of the valley floor. Each time a bend swings back to a shingle bank the river is at a lower level, and any portion of the bank that is not then removed remains as a terrace on the valley side. Such features are, of course, only short-lived, because as the valley is widened they inevitably disappear.

5. By the repetition of this widening process, as bend after bend migrates downstream, the spurs are all gradually cut away, and a trough-like valley with a nearly flat floor bounded by bluffs is developed (Plate 30). The shingle banks are now enlarged into broad embayments between successive bends. The beginnings of a flood-plain are thus established. During the continued development of this stage the river becomes graded and further deepening is then extremely slow.

MEANDERS

As the river continues to swing from side to side, it undercuts the bluffs wherever a bend impinges upon them, and so the widening of the valley floor proceeds, while the slopes above are slowly wasting away. The channel is now entirely in river

[H.M. Geol. Survey

(A) Alluvial deposits in the flood plain of Glen Feshie, Inverness-shire

[N. H. Darton, U.S. Geol. Survey

(B) Deposition from a heavily laden braided river. North Platte River, Nebraska–Wyoming boundary

[H.M. Geol. Survey

(A) Tidenham Bend, a meander of the River Wye, near Chepstow, Gloucestershire, with well developed bluffs (left) and slip-off slope (middle)

[E.N.A.

(B) Meanders of the Rio Grande, separating Mexico (behind) from United States territory (in front). Note ox-bow lake (bottom left)

deposits, bedrock being exposed only in and below the bluffs. Each part of the material deposited on the growing flood-plain is worked over in turn during the downward sweep of the bends, fresh additions from above constantly making good the losses by erosion and transport. The bends, now free to develop in any direction, except where they encounter the valley side, are more quickly modified. The stream is likely to be sluggish and easily turned aside by obstructions in the channel floor and by the inflow from tributaries. Freely developing bends are called *meanders* from their prevalence in the River Meander in Asia Minor.

As meanders of short radius are enlarged more rapidly

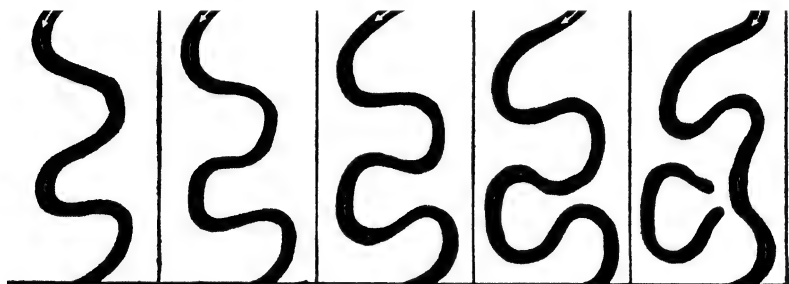



FIG. 75
Successive stages in the development of meanders, showing the formation of an ox-bow lake by the " cut-off " of a loop

than bigger ones, the curves all tend to have radii of about the same order. But as the curves develop by undercutting and deposition (Fig. 75), the meanders swell into loops which gradually approach until they coalesce. If a flood occurs when only a narrow neck of land is left between adjoining loops, the momentum of the increased flow is likely to carry the stream across the neck and thus short-circuit its course. On the side of the " cut-off " a deserted channel is left, forming an *ox-bow* lake which soon degenerates into a swamp as it is silted up by later floods (Plate 41B). By making artificial cut-offs (1927–37) the Mississippi River Commission has shortened a 331-mile stretch of the river by 116 miles. The natural short-circuiting process sets a limit to the growing radii of

meanders. Where the channel of the Mississippi is about half a mile wide, the meanders commonly have a radius of 4 or 5 miles. Narrower streams develop meanders of proportionately smaller radius (*cf.* Plate 85A).

As a result of this restriction on growth, a meandering river flows in a *meander-belt* (Fig. 76), which is usually about 15 to 18 times the width of the river. The meanders themselves swing down the belt with a snake-like motion. Relics of old

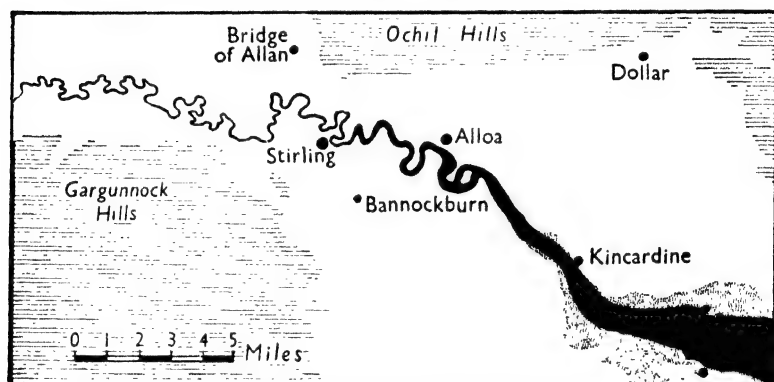



FIG. 76
Meander-belt of the river Forth. Horizontal shading indicates land above 400 feet

ox-bows, indicating the positions of former meanders, can be clearly seen from the air, although they may no longer be obvious on the ground. This is because the vegetation (reflecting the differences in soil and drainage) of an infilled ox-bow lake differs from that of the normal alluvium.

The valley reaches full maturity when its width is about the same as that of the meander-belt appropriate to the width of the river. As the bordering bluffs of the valley continue to be cut back where individual meanders impinge against them, the valley floor slowly expands until, after an immensely long period, it may attain a width several times that of the meander-belt. The latter then itself swings to and fro across the wide flood-plain, and old age has been reached. An interesting indication of the swing of a meander-belt was provided by the

discovery of the ruins of the ancient city of Ur of the Chaldees —the home of Abraham—in Mesopotamia. Five thousand years ago the Euphrates was 5 miles to the west of Ur; now it is 5 miles to the east of the ruins.

Flood Plains

If a stream is heavily laden with coarse debris from nearby mountains, its minimum gradient and rate of flow are necessarily greater than for one carrying finer material. As floods subside, bars and islands of shingle are left on the channel floor and the stream is obliged to divide into a network of many channels. Such a stream is said to be *braided* (Plate 40B).

Fig. 77

Schematic section across the flood plain of a stream bordered by natural levees

Thoroughly clogged rivers of this kind, much of the water of which flows below the surface through the interstices of the shingle, do not make meanders.

In the early stages of flood-plain development by streams less heavily charged with coarse debris, shingle-banks are deposited on the inner sides of bends, and these may gradually expand to form a deposit of river gravels over a wide area (Plate 40A). Later, however, when meanders are developing, the stream carries only sand, silt, and mud, and these are spread by floods as a veneer of alluvium over the coarser deposits of an earlier stage. Each time the stream overflows its banks the current is checked at the margin of the channel, and the coarsest part of the load is dropped there. Thus, a low embankment or *levee* is built up on each side (Fig. 77). Beyond the levees the ground slopes down, and in consequence is liable to be marshy. During floods, levees may grow across the junctions of small tributaries. The latter are then obliged to follow a meandering course of their own, often for many

miles, before they find a new entrance into the main river. Depressions occupied on the way become swampy. The characteristic features of a flood-plain thus include meanders, ox-bow lakes and marshes, levees, bordering swamps, and a complicated pattern of lateral streams.

Levees afford protection from ordinary floods, but the river then begins to silt up its confined channel with material that would otherwise have been spread as alluvium over the plain. Its level is raised, and the levees grow up with it, so that the danger from major floods becomes greater than before. To obtain increased protection artificial levees are often built, but these provide only temporary security, since they accentuate the tendency of the river floor to rise. In the flood-plains of the Po in Italy and of the Hwang Ho and Yangtze Kiang in China the built-up levees are locally higher than the neighbouring house-tops, and the rivers flow at a level well above that of the adjoining land. Such conditions are obviously extremely dangerous, as a severe flood may break through the levee and bring disaster to the agricultural lands over an enormous area. Along the Mississippi and its tributaries the flood danger is a serious menace. Little more than a century ago floods were easily controlled by levees about four feet high. The levees have since had to be raised several times. By 1927 they were three or four times as high, but nevertheless a great flood then broke through and devastated 25,000 square miles. Stronger levees up to 20 or 30 feet high have now been built, but it is clear that this method of flood control is far from satisfactory by itself. It can, however, be supplemented by reforestation of upstream regions (to reduce the rate of run-off), by the straightening and dredging of river channels, and by the allocation of certain areas as storage reservoirs for flood water.

The Mississippi floods, like many others, result from heavy rainfall in the early spring, supplemented by the melting of the winter's snow. If abnormal snowfall is followed by a widespread sudden thaw, so that all the tributaries rise simultaneously (instead of successively, as usually happens) a serious flood is inevitable. Disastrous flooding of the Euphrates occurred in 1929 as a result of the sudden melting of snow in

the Anatolean Mountains, a thousand miles from Baghdad. The Thames floods of the same year were due to abnormal rainfall supplemented by the effects of spring tides and strong gales blowing upstream. In rivers like the Indus great floods may also be caused by the release of vast quantities of water ponded back by great landslides which sooner or later collapse.

DELTAS

When a river reaches the sea much of its load may be quickly deposited, partly because the current is checked and partly because the salt water coagulates the fine particles. The sediment thus settles more rapidly than in fresh water. Waves and currents, however, may be sufficiently strong to sweep away the material and so prevent the mouth from being silted up. If, in addition, the land and sea floor are subsiding,

FIG. 78

Section through the sediments of a delta. T, topset beds ; F, foreset beds ; B, bottomset beds

or have recently done so, the valley will be partly submerged, and the river will pass into the sea by way of a tidal estuary.

On the other hand, if tides and currents are weak, as in enclosed seas like the Mediterranean and the Black Sea, deposition takes place at the mouth of the river on the sides and floor of the channel, and in front of it, so that a broad, outward-sloping fan of sediment is gradually built up on the sea floor. The front of each part of the fan grows seawards, just as a railway embankment is built forward during its construction, and the flood plain gradually extends seawards across its flat top (Fig. 78). While this is going on, and at a very early stage if the sea is shallow, the channel of the river becomes so choked and obstructed that it can no longer carry all the river water. The swollen river therefore breaks through or across

its banks, and so acquires two or more exits to the sea. This process of current bifurcation is repeated again and again, until a system of branching channels, called *distributaries*, is formed. The resulting seaward-growing terrace of sediment, traversed by distributaries, is a *delta*.

The Delta of the Nile was the first to be so named, because of the resemblance of its shape to the Greek letter Δ. It is an example of the *arcuate* type, with a rounded outer edge, modified in this case by fringing sand-spits shaped by sea currents

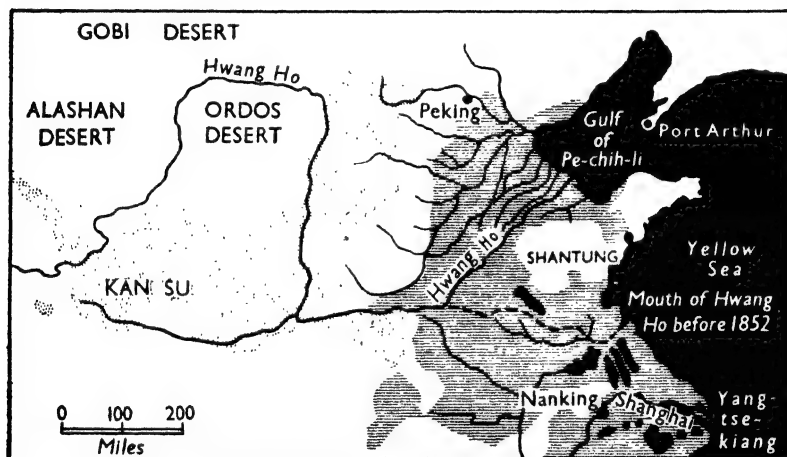



Fig. 79

Map of the Hwang Ho and its delta, showing the distribution of loess (dotted) and alluvium (horizontal shading) derived from loess (*After G. B. Cressey*)

(Fig. 135). After traversing a thousand miles of desert, the Nile has comparatively little water left when it reaches the Delta, and much of the load is deposited near the apex. Frontal growth is therefore slow. The Po delta extends more rapidly. Adria, now 14 miles inland, was a seaport 1,800 years ago, the average rate of advance thus indicated being about 40 feet a year. Ostia, the seaport of ancient Rome, is now four miles from the mouth of the Tiber. The richly fertile delta of the Hwang Ho in North China has grown across what was originally a broad bay of the Yellow Sea. A large island, now the Shantung Peninsula, has been half surrounded. Since

1852 the main branch of the river has emptied to the north of Shantung, but before then it flowed across the southern section of the delta and reached the sea about 300 miles from its present mouth. In that year and again in 1887 there were calamitous floods in which the loss of life from drowning and famine amounted to many hundreds of thousands (Fig. 79).

Most deltas, like those mentioned above, are arcuate. Their distributaries may be braided if the sediment deposited is coarse. If the sediment is finer, meandering courses tend to develop. The Mississippi, however, is exceptional in that

Fig. 80
The Mississippi delta : fifty years' growth

it extends its mouths seawards by way of deep channels, locally called "passes," which are outstretched like fingers. This part of its delta is the chief example of the *bird's foot* type (Fig. 80). The sediment brought down by the Mississippi contains an unusually high proportion of fine mud, and deposition is therefore mainly on the levee-like sides of the channels, thus confining them within impervious banks of clay. One such mouth is being extended 250 feet into the Gulf of Mexico every year.

The Mississippi delta is slowly subsiding. As deposition has kept pace with the sinking, thick accumulations of deltaic sediments have been built up. Borings prove a thickness up to at least 2,000 feet, and the low values of gravity—correspond-

ing to the low density of the underlying sediment—suggest that the actual thickness may be immensely greater. Similar accumulations of sediment, made possible by subsidence, are characteristic of most large deltas, including those of the Nile and Ganges-Brahmaputra.

Lakes, in which currents are negligible, provide highly favourable conditions for delta growth. When, in addition, their waters are salt, the rate of deposition from incoming rivers reaches its maximum. The Terek delta is at present growing outwards into the Caspian at the rate of 1,000 feet a year.

SUGGESTIONS FOR FURTHER READING

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Chapter XI

DEVELOPMENT OF RIVER SYSTEMS AND ASSOCIATED LANDFORMS

Tributaries and Drainage Patterns

A consequent stream is one whose original course is determined by the initial slopes of a new land surface. From a volcanic cone or an uplifted dome the first streams flow off radially. A long upwarp or geanticline provides a linear crest —the primary watershed or divide—with slopes on each side. In many cases the uplifted area consists of a coastal plain backed by an older land already drained by rivers. These continue down the new surface as *extended consequents*. If there is no " old land," the consequents begin some way below the crest, at each point where the drainage from above just suffices to initiate and maintain a stream. As the valley head widens and increased drainage is secured, each such stream is progressively lengthened by headward erosion. If uplift continues, the consequent streams are correspondingly lengthened by seaward extension.

As the consequents dig in, the valley sides furnish secondary slopes down which tributaries can flow. The tributaries lengthen by headward erosion, which picks out the least resistant parts of the rocks encountered, such as jointed or fractured belts, or beds of clay or shale. Subject to a general tendency to flow at right angles to the contours of the consequent valley, the pattern formed by tributaries and consequents thus depends largely on the nature and structure of the rocks which are being dissected. The latter may be homogeneous through a considerable depth, or they may consist of a stratified series of alternating strong and weak beds.

Where the rocks have no conspicuous grain and offer nearly uniform resistance to erosion, the headward growth of

[*South African Air Force*

FIG. 81

Aerial view of the dendritic drainage developed by insequent streams on massive granite. Tributaries of the Orange River near the Aughrabies Falls (see Fig. 69)

a tributary (beyond the slopes of the consequent valley) is governed primarily by the initial regional slope, with modifications controlled by haphazard irregularities of surface and structure. Because of these accidental controls such streams are said to be *insequent.* The regional slope, however, generally determines the prevalent direction followed by an insequent tributary ; it commonly makes an acute angle with the upstream part of the consequent valley. As each insequent stream develops its own valley, it receives in turn a second generation of tributaries. The branching drainage pattern so established is tree-like in plan, and is described as *dendritic* (Fig. 81). If the rocks are well jointed, however, a more rectangular pattern is likely to result.

Where, as commonly happens, the rocks consist of belts of alternately weak and strong beds, dipping seawards, the consequent valley is narrow and steep-sided where it cuts through resistant beds (sandstones, limestones, lavas, or sills), and broad

and open where it crosses outcrops of weak beds (clay or shale). A tributary beginning on weak rocks has a great initial advantage. Headward erosion guides it back along the weak bed, parallel to the strike. Such a tributary is called a *subsequent* stream. The rectangular drainage pattern formed by consequent streams parallel to the dip and subsequent streams parallel to the strike is described as *trellised* (cf. Fig. 85). Later tributaries add further detail to the trellised pattern.

Shifting of Divides and River Capture

The position of a divide remains permanent only if the rates of erosion are the same on each side, a state of affairs that is practically never achieved. It usually happens that the opposing slopes are unequally inclined, and that erosion is more effective on the steeper side. Consequently the divide is gradually pushed back towards the side with the gentler slope (Fig. 82). In primary divides this effect is most rapidly

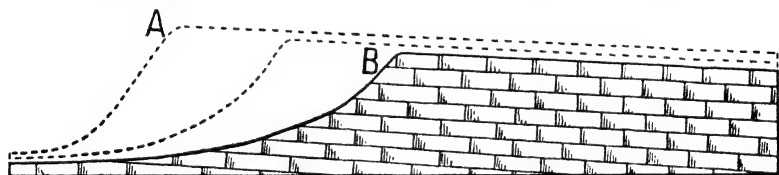



Fig. 82

Section to show the recession of a watershed from A to B as a result of the effect of unequal slopes on erosion

produced by headward erosion of the consequent valley-heads. As the latter work back through the crest, some from one side and some from the other, the divide becomes zigzag or sinuous, while the crest is notched and becomes increasingly uneven (Fig. 83). As deepening proceeds, the dissection of the ridge is steadily elaborated and the more resistant rocks between the valley heads stand out as peaks. Where the headward migration of one valley head encroaches on a valley head at the other side, the notch in the crest develops into a *col* or pass.

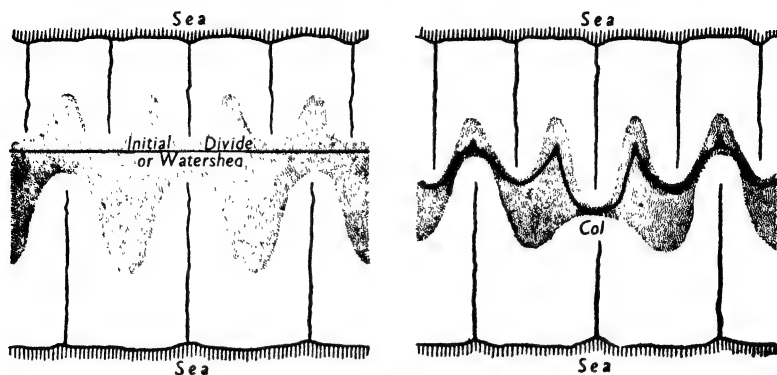



Fig. 83
Development of a zig-zag watershed by headward erosion

The new drainage area thus acquired by a headward growing consequent stream is generally of little importance. Migration of the secondary divides between neighbouring consequent valleys leads to far more revolutionary changes.

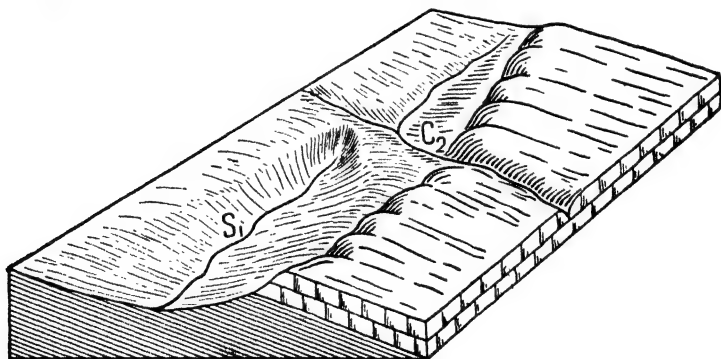



Fig. 84
Diagram to show impending river capture. The subsequent stream S_1 is cutting back at a relatively low level towards the consequent stream C_2

One of the original consequent rivers is likely to have a bigger drainage area than its neighbours—either because it flows through an undulation in the initial surface or because it is an extension of an earlier river in the "old land" behind the coastal plain—and the valley of this major stream is therefore

deepened and widened more quickly than the neighbouring consequent valleys. If the lateral divides are pushed back

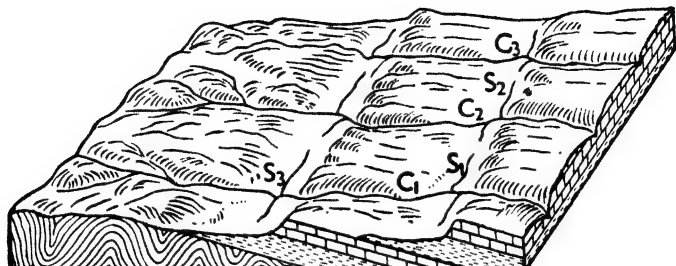



FIG. 85

Trellised drainage (consequent and subsequent streams), showing the dissection of a gently dipping series of hard and soft beds into escarpments and inner lowlands

until they reach these minor streams, the latter and their drainage areas are absorbed by the major river.

Capture of drainage on a still bigger scale becomes possible when the major river acquires vigorous subsequent tributaries, each working along a feebly resistant formation and each

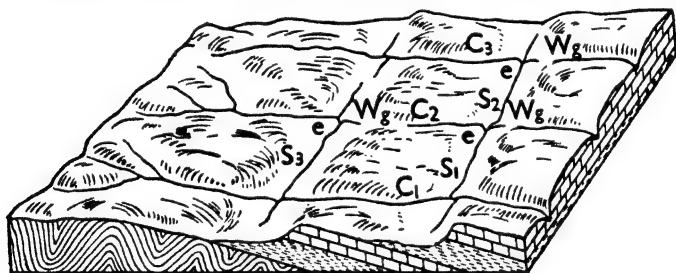



FIG. 86

Later development of the river systems of Fig. 85, illustrating river capture by the headward growth of the more vigorous subsequent streams

pushing back the secondary divide at its head (Figs. 84 and 85). Endowed with a relatively low local base-level, a deeply entrenched subsequent, *e.g.* S_1 in Fig. 86, cuts back towards a consequent C_2, which is still draining an area at a higher level. Eventually C_2 is intercepted, its headwaters are diverted into S_1, and its lower course is beheaded. This process is

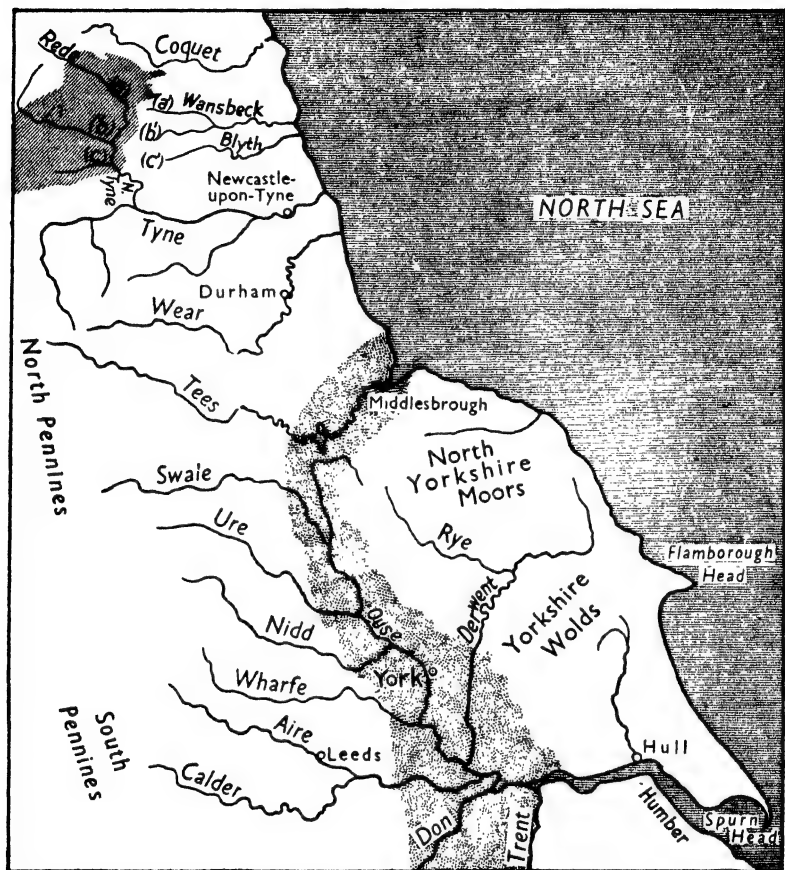



Fig. 87

River systems of North-east England, to illustrate river capture by the Ouse (along the outcrop of the soft Triassic beds—*dotted*) and by the North Tyne (along the outcrop of the Scremerston Coal Group—*inclined shading*)

called *river capture.* The rectangular bend *e* at the point of diversion is known as the *elbow of capture.* The beheaded river, now deprived of much of its drainage, is described as a *misfit,* since its diminished size is no longer appropriate to the valley through which it flows. Its new source is some way below the elbow of capture and the deserted notch, *Wg,* at the head of its

valley becomes a *wind gap*. A subsequent stream S_2, which originally entered the captured stream near or above the elbow, now has its local base-level lowered to that of S_1. It is thus enabled to deepen its valley and to extend backwards until it, in turn, reaches and beheads the next consequent, C_3. A major consequent river, with the aid of its subsequents, may therefore acquire a very large drainage area at the expense of its neighbours.

The rivers which flow into the estuary of the Humber illustrate the development of an actual river system by the process of capture outlined above. The uplift of the Pennines provided the slopes down which a number of consequent streams flowed into the North Sea. Of these only the Aire still maintains an uninterrupted course. The Wharfe, Calder, and Don were probably tributaries of the Aire from the start. The Nidd, Ure, and Swale, however, have each been captured in turn by the Ouse, a powerful subsequent stream which worked back northwards along the soft strata of the Trias (Fig. 87). On the eastern side of the Ouse it is difficult to trace the former courses of the beheaded streams, because of uplift of the Cleveland Hills and obliteration of the older valleys by glacial deposits. A more diagrammatic example is provided by the rivers of Northumberland. The three main streams, *a*, *b*, and *c*, of the North Tyne system clearly correspond to the Wansbeck, *a′*, a tributary of the Wansbeck, *b′*, and the Blyth, *c′*. The headwaters of the forerunners of these were captured by the North Tyne, a subsequent of the Tyne, as it worked back along the soft beds of the Scremerston Coal series.

River capture by subsequents which developed along the clay formation known as the Gault has greatly modified the drainage of the Weald. Examples can easily be recognised in a map of the region.

Escarpments and Related Features

The valley of a subsequent stream is widened and deepened between divides formed by the bands of resistant rock on either side. As the weak bed is gradually worn away, the upper

surface of the underlying resistant bed is uncovered, and on this side the valley slope therefore approximates to the dip. On the other side the overlying resistant bed is exposed at its base and, as a result of undercutting and the falling away of joint blocks, it soon begins to stand out as a prominent ledge which steepens into an *escarpment*, facing inland (Fig. 88). As the subsequent stream, keeping pace with its consequent, continues to deepen its valley in the weak rocks, its channel gradually shifts in the direction of dip, that is, towards the escarpment. The latter is thus steadily worn back, leaving a gentle dip slope on the other side of the valley. The valley itself, as it becomes wide and extensive, develops into an *interior lowland.* Small tributaries, known as *obsequent* streams,

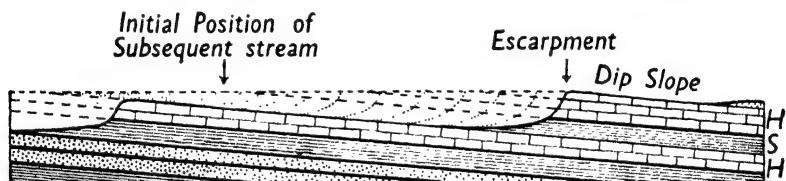



FIG. 88

Stages in the development and recession of an escarpment
H = hard, resistant formations S = soft, easily eroded formations

descend the escarpment, others, called *secondary consequents,* flow down the dip slope, and both sets add to the trellis pattern of the drainage (*cf.* Fig. 85).

Fig. 48 illustrates the succession of escarpments and interior lowlands between Gloucester and the London Basin. From the Lias clays and marls of the Severn valley the escarpment of the oolitic limestones of the Jurassic rises to the crest of the Cotswolds. The Oxford Clay is responsible for the interior lowland occupied by the Thames above and below Oxford. A minor escarpment, that of the Corallian limestone, is then followed by the interior lowland of the Kimmeridge Clay. Beyond this the Chiltern Hills represent the escarpment of the Chalk, the dip slopes of which lead down to the London basin (Fig. 57). The Chalk escarpment curves round to the eastern side of the Wash, and continues to the north as the Lincolnshire

[H.M. Geol. Survey

(A) Escarpment of Carboniferous Limestone, Eglwyseg Mt., north of Llangollen, Denbighshire

[T. S. Lovering, U.S. Geol. Survey

(B) Hogback of Dakota Sandstone (Cretaceous). Foothills east of the Front Range, Rocky Mountains, Colorado

[H.M. Geol. Survey

(A) Alluvial terraces of the River Findhorn, Nairn

[A. M. Cockburn

(B) Alluvial terraces of the Frazer River, British Columbia

RIVER TERRACES

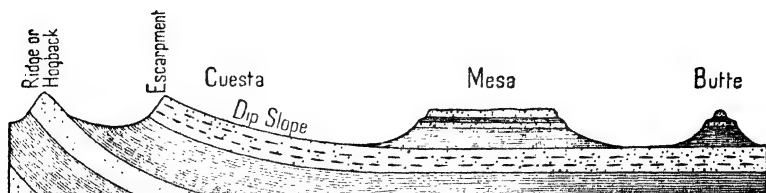



Fig. 89

To show the relation of various erosional landforms to the structure and dip of the strata from which they are carved

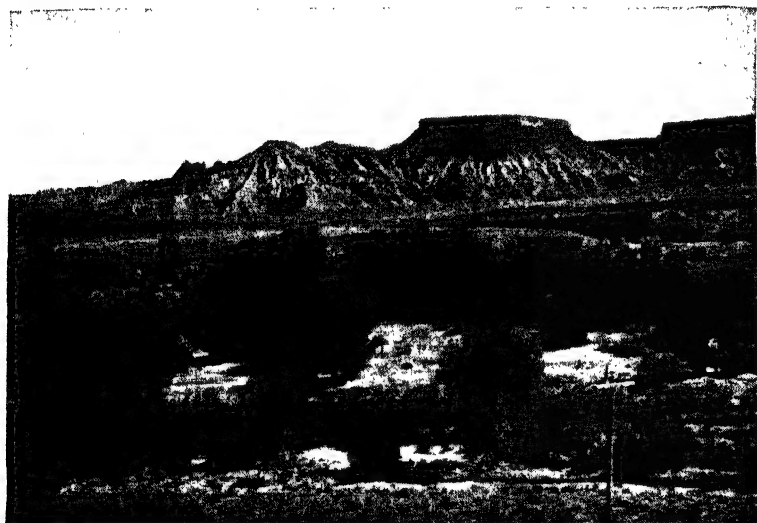
and Yorkshire Wolds. On the south side of the London basin the Chalk again emerges as the great escarpment of the North Downs which, less conspicuously, swings round the Weald

[Grant, U.S. Dept. of Interior

Fig. 90

Mesa showing marginal "badland" erosion where the protective cap has been removed. Zion National Park, Utah

to appear again on the far side as the South Downs. For illustrations of other escarpments see Plates 18 and 42A.

An escarpment and its dip slope together form a feature for which there is no English name. The Spanish term *cuesta*

(pronounced *questa*) has therefore been adopted. If the beds dip at a high angle, the dip slope becomes as steep as the escarpment and the feature corresponding to the cuesta is simply a ridge or *hogback* (Plate 42B). At the other extreme, in horizontal beds, the cuesta becomes a *mesa* (Spanish for table), that is, a tableland capped by a resistant bed and having steep sides all round. Table Mountain, behind Cape Town, is a small but high mesa which has been developed by erosion from a fault-block. By long continued wearing back of the sides, a mesa dwindles into an isolated flat-topped hill. In America such a hill is called a *butte*, from its resemblance to the butt or bole of a tree, and the term has been widely adopted. In Western America buttes commonly occur where the beds dipping off the mountain flanks flatten out (Figs. 89 and 90). In South Africa, however, similar residual landforms, many of which are capped by isolated relics (outliers) of once continuous dolerite sills are called *kopjes*.

Superimposed Drainage

In many regions ancient folded rocks are now exposed which were formerly hidden beneath an unconformable cover of later sedimentary formations. The rivers initiated on the cover, with a drainage pattern appropriate to its structure, ultimately cut their valleys into the underlying rocks, maintaining their courses with little or no relation to the very different structures in which they then find themselves. As the cover is gradually removed by denudation the old rocks are exposed over a steadily increasing area, the drainage pattern of which has been *superimposed* on it as an inheritance from the vanished cover.

The clearest example of superimposed drainage in Britain is afforded by the rivers and lakes of the Lake District. As illustrated in Figs. 91 and 92, the Lake District consists of an oval-shaped area of Lower Palaeozoic rocks (folded during the Caledonian orogenesis and having a general trend from E.N.E. to W.S.W.) enclosed in a frame of Carboniferous Limestone

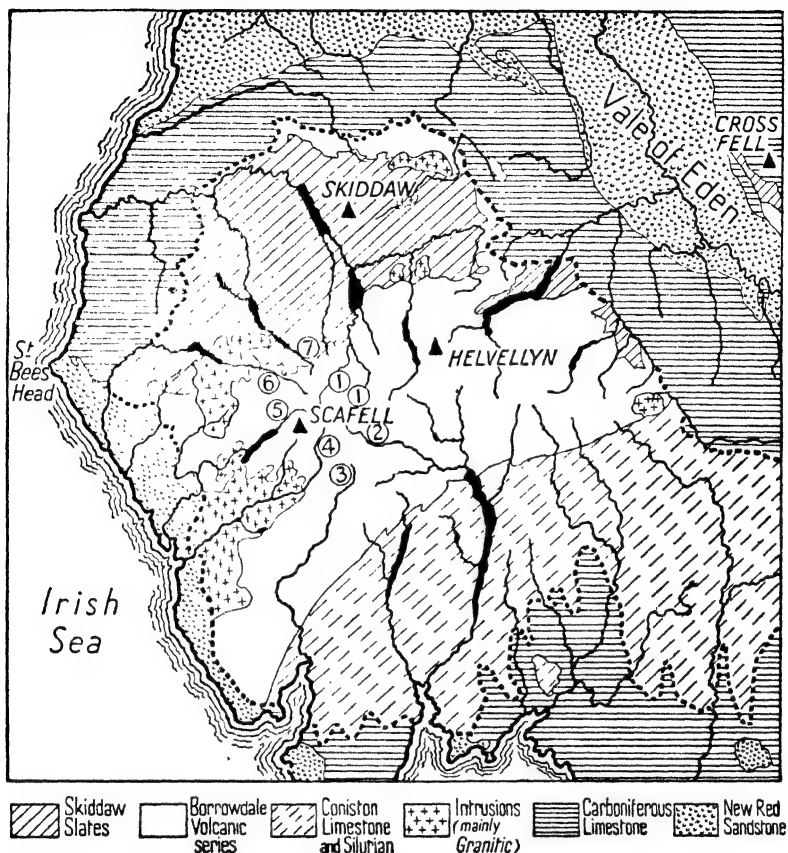



FIG. 91

Geological sketch-map of the Lake District, showing the radial pattern of the superimposed drainage

and New Red Sandstone, the beds of which everywhere dip outwards. The younger formations originally covered the older rocks. During Tertiary times the region was uplifted into a slightly elongated dome, with its axis curving towards the east from a culminating point which lay above the present summit of Scafell. The consequent streams that flowed radially down the slopes of the dome still persist in the older rocks. The radial pattern of the valleys and mountainous

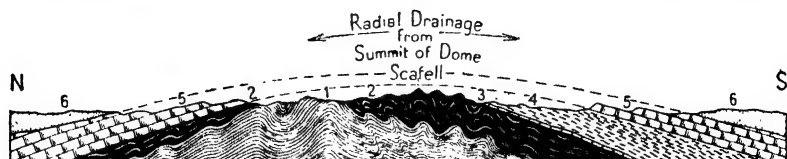



Fig. 92

Section across the Lake District

(1) Skiddaw Slates (2) Borrowdale Volcanic Series (3) Coniston Limestone
(4) Silurian (5) Carboniferous Limestone (6) New Red Sandstone
(Igneous intrusions omitted)

ridges centred near Scafell is particularly striking. As numbered on Fig. 91, the valleys are (1) the headwaters of Borrowdale and Derwentwater ; (2) Langdale and Windermere ; (3) The Duddon ; (4) Eskdale ; (5) Wasdale and Wastwater ; (6) Ennerdale ; and (7) Buttermere and Crummock. To the east, the streams leading into Coniston, Ullswater, and Haweswater flow off the axis towards the north ; and another set of streams, some feeding Windermere and others draining directly into the Irish Sea, flow southwards. The lakes and many of the other scenic features of the Lake District have resulted from glaciation.

The Appalachian rivers of the United States are now interpreted as an example of superimposed drainage. Long after the folding of its Palaeozoic rocks, the Appalachian belt was worn down and buried beneath a cover of marine sediments. Later the region was uplifted, consequent streams flowed down the slopes of the cover into the Atlantic, and eventually cut their valleys into the foundation rocks. The cover has now vanished, and the Appalachians have been dissected into long mountainous ridges, but the main rivers continue to cross the latter through deep " water gaps." Examples of these great notches cut through the apparent barriers are the Hudson gorge in the Highlands of New York State ; the Delaware Water Gap (Fig. 93) farther south ; and the gap of the Potomac at Harper's Ferry, famous during the Civil War as the strategic gateway into the broad interior valley of the Shenandoah.

[U.S. *Geol. Survey*

Fig. 93

Delaware water gap, cut by the Delaware River (Pennsylvania-New Jersey boundary) through a tilted formation of resistant conglomerate

The Normal Cycle of Erosion

It has now been made abundantly clear that rivers, and indeed all landscape features, are continually changing. From the time when the sculpturing of a newly uplifted land area begins, the valleys and associated landforms pass through a series of well characterised stages, referred to as youth, maturity, and old age, until, if sudden interruptions due to earth movements do not intervene, the whole area is reduced to a peneplain. The whole sequence of the changes involved in this evolutionary development of landscapes is called the *normal cycle of erosion* (Fig. 94), the term "normal" implying that the development is controlled by river action and surface erosion under humid conditions. The cycle concept—perhaps the most fertile ever contributed to geomorphology—was later applied by W. M. Davis, its originator, to the distinctive landforms developed by erosion under glacial and arid conditions.

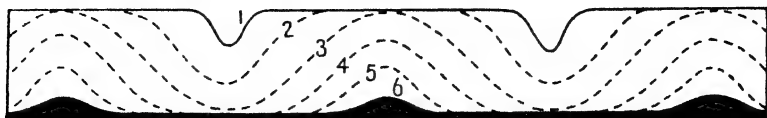



FIG. 94

Profiles across an initially uptilted block showing successive stages in the cycle of erosion. 1–2, youth ; 3–4, maturity ; 5–6, old age

A river system may be still youthful in its upper tracts, while the characteristics of maturity have already been reached lower down and may, indeed, have passed into the monotonous features of old age towards the sea. The completion of each stage is first attained in the lower tract, and slowly creeps inland. In the course of a full cycle rivers and landscapes have a relatively short but vigorous youth, a much longer period of mature development, and an extremely long old age of decline and degeneration (Fig. 95). The actual time required for a cycle to run its course in any given area naturally varies enormously with the height and structure of the uplifted area, and with the size of the rivers and their drainage basins. A million years or so may suffice to bring comparatively small rivers, like those of Britain, well into the stage of old age, but the great rivers of high Asia may still be far from completing their prodigious task in a hundred million years.

The stage of *youth* ideally begins with the dissection of a featureless plateau or an undulating folded region. It is essentially the period during which the valley form is undergoing vigorous development, especially in depth and headward growth. The early rivers flow swiftly and have irregular gradients. Lakes, rapids and waterfalls, and gorges are highly characteristic features. In recently folded regions the main rivers occupy synclinal furrows. Tributary development proceeds rapidly during youth and river capture is common. The streams compete for space until the victorious ones acquire well defined valleys and drainage areas. Between the valleys there are at first extensive tracts of the original surface, poorly drained and often swampy. As the valleys widen, and the divides are pushed back, the areas of these tracts gradually

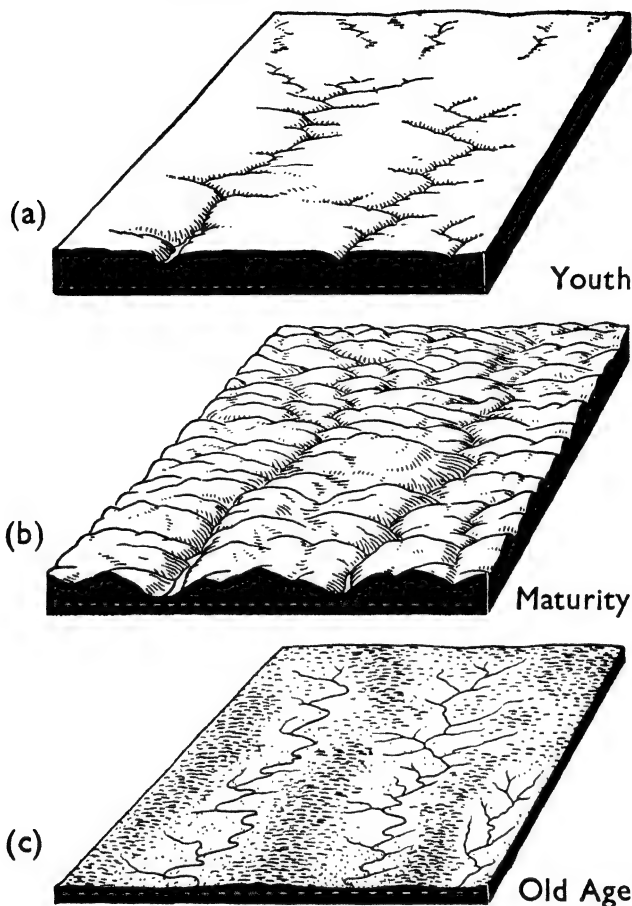



FIG. 95
Wearing down of land surface from youth (*a*) through maturity (*b*) to old age (*c*)
(*After V. C. Finch and G. T. Trewartha*)

diminish. The youth of the landscape merges into maturity when the relief attains its maximum amplitude. The area is then " all slopes " (stage 3 in Fig. 94), the last traces of the initial surface disappearing as the summits of the divides begin to be worn down. River systems reach the end of the youthful stage when the main stream and its chief tributaries become

graded, that is, after lakes, waterfalls, and rapids have been eliminated, and gorges have widened into V-shaped valleys. Most lakes disappear during early youth, but exceptionally deep ones, like the Great Lakes of North America, survive much longer. It may happen, of course, that grading of a river system is not fully established for some time after the initial surface has vanished. The land surface will then have reached maturity before the rivers have completed their youth. Generally, however, when rivers still obviously in their infancy traverse a landscape which is long past its youth, the contrast is due to uplift of an area already dissected by an earlier but uncompleted cycle.

At the beginning of the stage of *maturity* the divides are at their maximum height above the valley floors, and the valleys have reached their maximum width, as measured from divide to divide. Thereafter, the upland surfaces are slowly lowered, but slow as this drawn-out process may be, it is faster than the lowering of the graded valley floors. Subsidiary tributaries still develop, and some rivers may continue to increase their drainage basins by the capture of neighbouring streams. As the topography gradually becomes more subdued, the mountain peaks of the greater ranges and the hills of the subsidiary ridges are rounded off into broadly sweeping curves, the convex summits passing into concave and graded slopes which lead down to the bordering bluffs and flats of the valley floors. The latter are increasingly widened by lateral erosion ; meanders are characteristic, and alluvial plains become extensive. In youth the flat surfaces of the landscape are those of the initial surface (apart from the lacustrine flats of infilled lakes), whereas in maturity the flat surfaces are the valley floors. Near the sea the divides between the flood plains of neighbouring rivers may be completely worn down to plains of bedrock mantled with rock-waste. Here chemical weathering becomes dominant and deep soils develop. The flood plains gradually coalesce and extend inland at the expense of the wasting divides. In this region old age has already begun.

There are no distinctive features in terms of which the the close of maturity can be clearly defined, but *old age* is

generally considered to have set in when the valley floors reach a width several times that of the meander-belt. The widening of the valley floors by lateral erosion, and the lowering of the divides by chemical weathering and surface creep, continue as before, but ever more slowly as base-level is approached over a wider and wider area. The process may become almost infinitely slow, but so long as streams can carry a load, even if it be mainly in solution, the reduction of the land towards base-level proceeds indefinitely. The uplands of youth and the maze of slopes of maturity are replaced in old age by widespread lowlands, rising gently inland. The region has become a *peneplain*. Over sedimentary rocks the relief is uniformly faint. But in geologically complex orogenic belts the peneplain developed across their crystalline roots is rarely, if ever, brought to such perfection. The more stubborn rocks, such as the most resistant parts of granite stocks and batholiths, continue to stand out as occasional residual hills. Such erosional survivals are called *monadnocks*, after Mount Monadnock in New Hampshire, which is a typical example of its class. In sedimentary regions penetrated by volcanic necks, the latter may long persist as monadnocks.

For the perfect development of a peneplain it is essential that the area should not be uplifted. Few regions of the present lands have escaped recent earth movements, and present-day peneplains of considerable extent are therefore rare. Western Siberia and the country around Hudson Bay are noteworthy examples of peneplains, but even these have had their surfaces modified in detail by glaciation.

The Isostatic Response to Denudation

The reduction of a region to a peneplain involves the removal of an immense load of material, the mass of which is proportional to the height of the initial surface. While the crust was being thus unloaded by denudation, slow isostatic uplift must have been continuously in progress, thereby giving the rivers more work to do and delaying its completion. This

effect has so far been tacitly ignored for the sake of simplicity of treatment, but it should not be overlooked.

Let us suppose that a thickness of 1,000 feet of rock having an average density of 2·6 has been removed from a region while isostatic equilibrium is maintained and no independent earth movement occurs. The mass lost is proportional to $2{\cdot}6 \times 1{,}000$, and this must be made good by the inflow at depth of a thickness h of material with a density of about 3·4. The condition for the maintenance of isostasy is that $3{\cdot}4h = 2{,}600$ feet; whence $h = 765$ feet. This influx of sima raises the plane AB (Fig. 96) to A′B′, and the new surface is only 235 feet below the original level of the denuded block of country. For the development of

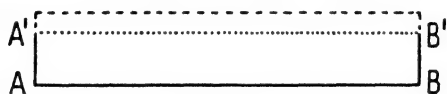



FIG. 96

Isostatic response to denudation : uplift of plateau

FIG. 97

Isostatic response to denudation : uplift of mountain peaks

a peneplain from an initial surface which stood 1,000 feet higher, the thickness of rock to be removed is not 1,000 feet, but about four times as much.

Such uplift must be considered a normal accompaniment of a cycle of erosion. It involves the curious effect that during late youth and early maturity the summits of peaks and divides become elevated above the initial surface. This is illustrated by Fig. 97. When the cross-sectional areas of valleys and divides are equal, half the mass of the denuded block has been removed. The plane CD will by then have been raised to C′D′, *i.e.* by 765/2 feet, assuming the summits to be 1,000 feet above the valley floors. The bearing of this remarkable result on the high altitudes of the Himalayan peaks is referred to on page 201.

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FIG. 98

The sky-line of the Grampians (the Mamore Forest), looking S. from Ben Nevis. An example of an uplifted peneplain, now deeply dissected

UPLIFTED PENEPLAINS

The isostatic uplift that accompanies denudation is, of course, not competent to uplift a peneplain once it is formed. It has merely delayed peneplanation. The uplifts referred to here and in later sections are those due to independent earth movements.

Peneplains representing the practically completed cycles of former periods, but since uplifted to form the initial surfaces of later or present-day cycles, can be detected in many landscapes. In the Grampian Highlands an old peneplain, now dissected into a landscape of late youth or early maturity (though modified by glaciation), is easily recognised by the even skyline corresponding to a widespread uniformity of summit levels at about 2,000 feet (Fig. 98). The occasional higher peaks which rise above this " summit plane " represent

the monadnocks of the old peneplain. A similarly dissected uplifted peneplain is represented in Wales by a summit plane at 1,500 to 2,000 feet. These old peneplains are distinguishable from uplifted coastal plains by the fact that they truncate a great variety of orogenic structures.

A marked tendency to rise at intervals has controlled the geological history of the interior of Africa for many hundreds of millions of years. Several cycles of erosion are recorded by enormous thicknesses of continental sediments and by uplifted peneplains now represented by plateaus surmounted by monadnocks of the inselberg type (page 274).

A peneplain approaching completion during the Miocene was uplifted, warped, and rift-faulted at the close of the Miocene, and again at the end of the Tertiary, to form the great plateau of Tanganyika and adjoining territories (page 431). It now stands at a height of 3,000 to 6,000 feet, and inselbergs which rise from its surface are the residual hills from an earlier peneplain uplifted during the Jurassic. The faulted borders and some of the rift valley scarps are deeply notched by gorges and canyons with waterfalls at their heads. The Kalambo Falls, the most celebrated example, came into existence on the eastern fault-scarp of the Tanganyika rift. They have now cut back three miles from the lake, and there the placid stream above the head of the gorge suddenly takes a single leap of 705 feet over the brink (Fig. 99).

Farther south the interior plateaus of the Basuto Highlands and the High Veld behind Natal were formed by the uplift of a Cretaceous peneplain during late Cretaceous and Tertiary times. These movements were accompanied by depressions of the coastal area. An enormous escarpment has since been worn back into the plateau country, which reaches a height of 12,000 feet in the basalt-capped Drakensberg of Natal (Plate 87A). On the plateau side of the escarpment the headwaters of the Vaal and Orange Rivers begin their long journey to the Atlantic, while the shorter rivers of Natal begin as mere trickles which descend the escarpment. Not far from its source the Tugela River plunges over the brink of a precipitous amphitheatre in the escarpment. Five clear leaps with inter-

[*Capt. J. Brown*

FIG. 99

The Kalambo Falls, east of Lake Tanganyika, Northern Rhodesia

vening cascades make up a total drop of 2,810 feet. The Tugela Falls, though of insignificant volume, are probably the highest in the world. The Great Escarpment, as it is called, can be traced all round South Africa. It everywhere faces the marginal lowlands and marks the edge of the plateaus of the interior.

Interruptions in the Cycle of Erosion

At any stage in an uncompleted cycle the normal sequence of changes may be interrupted by earth movements of uplift or subsidence (often accompanied by faulting), by volcanic action, or by changes of climate leading to glaciation, increased rainfall, or aridity. The distinctive landscape features developed under glacial and desert conditions are described in later chapters. It should be noticed, however, that glaciation is complicated by associated effects due to (*a*) abstraction of water from the sea to form ice-sheets and its subsequent restoration when the ice melts away, with corresponding changes in sea level and consequently in base level ; and (*b*) isostatic depression due to the loading of an area by an ice-sheet, followed by uplift when the ice-sheet retreats and disappears.

Volcanic activity may introduce local accidents, such as the obstruction of a valley by a lava flow. Youthful features are then temporarily restored while the river is regrading its course through the obstacle. On a larger scale whole landscapes may be buried beneath a thick cover of plateau basalts, in which case a new cycle then begins on the volcanic surface.

If a region is depressed by earth movements, its surface is brought nearer to base level, the work to be done by erosion is diminished, and the stages of the cycle then in progress are passed through more quickly. When a depression is localised across the course of a river a lake is formed (see page 432). When coastal regions subside—unless sedimentation keeps pace, as in subsiding deltas—the sea occupies the lower reaches of valleys and estuaries are formed. Tributaries which entered the valley before it was drowned now flow directly into the tidal waters of the estuary and become *dismembered streams.* Rivers like the Thames and Humber are sufficiently powerful to keep their channels open. The sluggish rivers of old age, however, may be unable to prevent the growth of obstructive bars and spits across their estuaries, and the latter then become silted up. The Broads of East Anglia occupy the site of a

former estuary which has already been largely obliterated in this way. The rivers now flow between levee-like embankments of sediment deposited along their sides, and thus they have become separated, except for local channels, from the shallow waters of the intervening broads.

The remaining sections of this chapter are devoted to outstanding features, such as river terraces, incised meanders, and canyons, developed by rivers in response to uplifts which are rapid compared with the slow secular uplift involved in the maintenance of isostasy. As a river is raised further above its base level, the work to be done by erosion is increased, and the river is obliged to begin afresh the task of grading its course. The river has been *rejuvenated* and, as a further consequence, the landscape is correspondingly *revived.* The change begins where the gradient is steepened, with the restoration of youthful features such as rapids, and gradually works upstream. The newly deepened part of the valley is sunk as a gorge or narrow V in the wider V or trough-shaped floor of the pre-existing valley. The cross-profile shows a marked change of slope where the earlier valley form is intersected by the new. Above the point to which the new features have receded—commonly marked by a step or " knick " in the long-profile—the river and its valley retain their former characteristics. The knick-point is most marked when the uplift has been even ; it may not be developed if the elevation was brought about by gentle tilting.

River Terraces

When a river that has already established a flood-plain is rejuvenated, it cuts through its own deposits into the underlying rocks. The sides of the original alluvial plain are then left as flat terraces above the new level of the river. In the course of time the new valley is widened and a second flood-plain forms within the first one, of which only local remnants may survive. By subsequent uplift and rejuvenation a second pair of terraces may then be left on the valley side. The sides of many of the lowland valleys of Britain (Plate 43A) and

Western Europe—and indeed in many other parts of the world—are bordered by a series of such river terraces, each corresponding to a phase of valley widening and deposition, following one of uplift (relative to sea level), rejuvenation, and valley deepening. A typical terrace is a platform of bedrock thickly veneered with a sheet of river-gravel and sand passing upwards into finer alluvium.

As illustrated in Fig. 100, the Thames has three terraces : (1) The *High* or *Boyn Hill Terrace*, named after a locality near Maidenhead, where it is well preserved. The gravels, mostly composed of flint, contain the fossil remains of extinct species of elephant, hippopotamus, and rhinoceros. The climate indicated was warm and genial. Man had already appeared, as palæolithic flint implements are also found. (2) The *Middle*

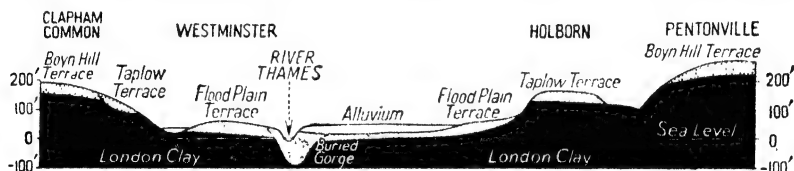



FIG. 100

Section across London to show the paired alluvial terraces of the River Thames (*After H.M. Geol. Survey*)

or *Taplow Terrace.* Bones and skulls of lions and bears occur in the lower deposits, but nearer the surface these are absent, and remains of the hairy mammoth appear. The change points to the oncoming of the most recent phase of the ice-age. (3) The *Low* or *Flood-plain Terrace.* Here the mammoth is still found, accompanied by reindeer and elk. These fossils, as well as those of Arctic plants, indicate a thoroughly frigid climate. During continued uplift the Thames cut a gorge which was ultimately filled with gravel when a later subsidence brought the valley to near its present level. A boring into the gorge-gravels at Charing Cross failed to find bottom at 80 feet below the river. Highly polished neolithic implements occur in the deposits overlying the gorge. Excavation of the London Docks has revealed the presence of three beds of peat containing relics of oak and beech. Above the oldest of these fossil forests

the first signs of the Bronze Age appear. And so we reach the "made ground" of historical times, and the alluvial meadows and marshes of the present day.

Incised Meanders and Gorges

If, at the time of rejuvenation, a stream was meandering on a valley floor underlain by resistant bedrock, with only a thin cover of easily eroded mantle deposits, if any, the deepening channel is etched into the underlying rocks, while the

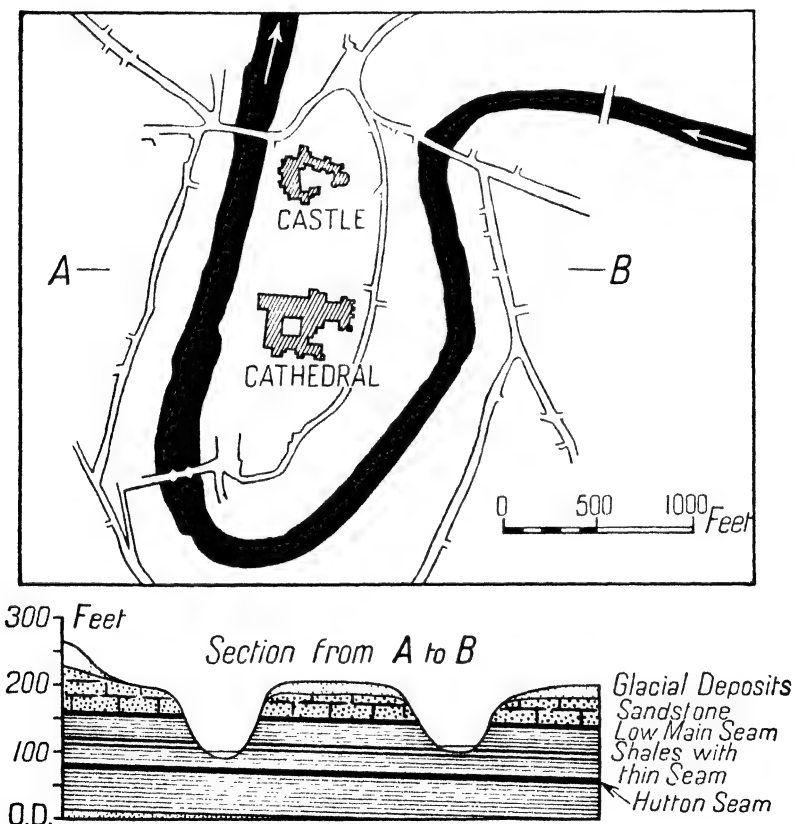



Fig. 101

Map and section showing the incised meander of the River Wear at Durham

original winding course is still preserved. In this way *incised* or *entrenched* meanders are produced. The " hair-pin gorge " of the Wear at Durham is a familiar British example (Fig. 101). A well-protected site within the loop was selected for the cathedral, which is thus enclosed by the gorge on three sides. The fourth and easily vulnerable side was safeguarded by building a castle there.

The change of form of incised meanders, and the wearing back of the confining walls are relatively slow processes controlled by lateral undercutting of the river banks. Localised

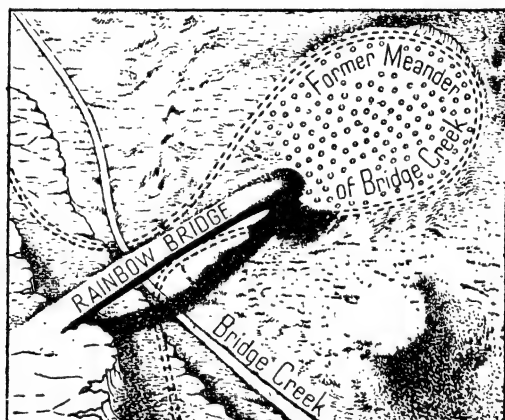



Fig. 102
To illustrate the origin of Rainbow Bridge, Utah (see Plate 44B)

undercutting on both sides of the narrow neck of a constricted loop sometimes leads to the formation of a natural bridge. On each side of the constriction a cave is worn, especially if the rocks at river level are weak. Eventually the two caves meet, and the stream then flows through the perforation. The stronger rocks of the roof remain for a time as an arch spanning the stream, and the loop-shaped gorge at the side is abandoned. In Utah, where recent uplift has made possible the development of many deeply incised meanders (Plate 44A), there are several examples of such arches. The most impressive of these is Rainbow Bridge (Plate 44B and Fig. 102), a

graceful arch of sandstone which rises 309 feet over Bridge Creek in a span of 278 feet.

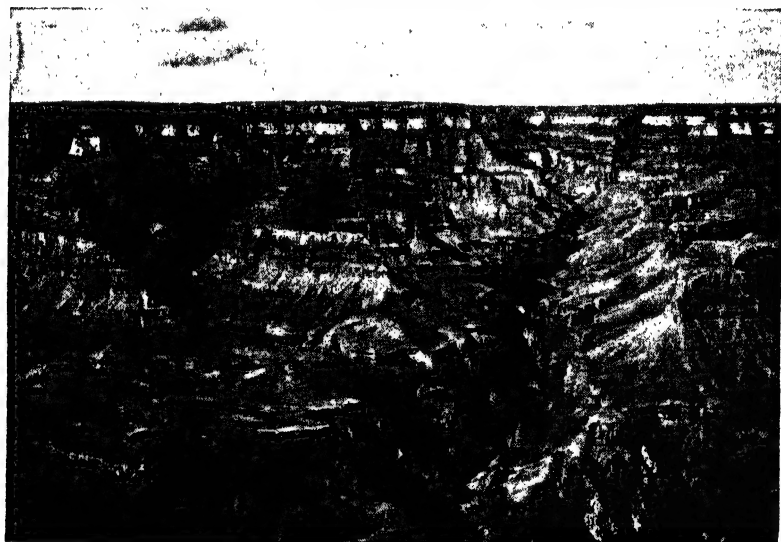
Bridge Creek is a tributary of the Colorado River, and is thus related to one of the world's most awe-inspiring scenic wonders—the Grand Canyon of the Colorado (Plate 1). Towards the end of Tertiary times the region which is now the high plateau of northern Arizona and southern Utah had been reduced to a land of old age topography traversed by a valley,

[*U.S. Geol. Survey*

FIG. 103
Grand Canyon of the Colorado

50 miles wide or more, margined by mesas and buttes on the north and by lava plains and cones on the south. A late Tertiary uplift of 6,000 to 8,000 feet then rejuvenated the old river, and the cutting of the Grand Canyon began. From the Rocky Mountains of Colorado in the east the river receives sufficient water to carry it successfully through hundreds of miles of desert country.

The Canyon has now reached a maximum depth of 6,250 feet, but downward erosion by the heavily laden river is still actively in progress. A narrow inner gorge has been cut

through a thousand feet of crystalline rocks (Fig. 70). The walls above, carved through a nearly flat Palæozoic cover of strong sandstones and limestones alternating with weak shales, rise by a succession of steps and slopes of varied colours which add to the architectural grandeur of the scene. As a result of this differential erosion under arid conditions the width of the Canyon from rim to rim is now 5 to 15 miles. During the recession of the walls bold spurs between the bends have been carved into pyramids and isolated pillars (Fig. 103). The plateau is trenched by several tributary canyons, but otherwise the general surface is but little dissected. The present cycle is still in the stage of early youth (see Plate 84B).

Antecedent Drainage of the Himalayas

During the uplift of a great mountain range it may happen that a river which was already flowing across the site of the future mountains continues to deepen its valley while the uplift is in progress, so that it becomes permanently entrenched in the rising landscape. A continuously rejuvenated river which thus succeeds in maintaining the slope of its channel from a source behind the mountains to the plains in front is called an *antecedent* river, to express the fact that the river was in existence before the mountains which have risen across its course.

By far the most remarkable examples of antecedent rivers are those which cross the Himalayas. The watershed is not along or near the highest peaks, as might have been expected, but well to the north in Tibet. From their upper courses on the plateau the Indus, Bramaputra, and many of the head-waters of the Ganges traverse the ranges by way of deep gorges cut in the bottom of steep V-shaped valleys. As the Indus passes through Gilgit in Kashmir, the river itself is only 3,000 feet above its delta, but the precipitous walls by which it is confined rise to heights of nearly 20,000 feet. Like a gigantic saw the river has cut through 17,000 feet of rock, keeping pace with a like amount of uplift.

[*Dorien Leigh, Ltd.*

(A) Incised meanders of the San Juan River, Monument Valley, Utah

[*Dorien Leigh, Ltd.*

(B) Rainbow Bridge, Bridge Creek, Utah (see Fig. 102)

[*Aircraft Operating Co. of Africa*

(A) Aerial view of the ice cap on the Kibo summit (19,321 feet)

[*Dorien Leigh, Ltd.*

(B) View from the plateau at about 3,000 feet

KILIMANJARO, TANGANYIKA TERRITORY

The River Arun, a tributary of the Ganges, rises in Tibet at a height of 22,000 feet, and passes through a stupendous gorge between Everest (29,140 feet) and Kangchenjunga (28,146 feet), the rocks of which were originally continuous. It could not have done this with the mountains at their present heights. The erosion has been persistently downwards rather than headwards, and there are no important waterfalls. Wager, who has made a special study of the Mt. Everest region, has suggested that the great peaks of the Himalayas owe much of their exceptional elevation to the additional effect of isostatic uplift of the kind discussed on page 190. Instead of a 1,000-foot block carved into hills and valleys, we have here a 16,000-foot block, and the corresponding isostatic uplift would therefore be more than 6,000 feet. Denudation of the Himalayas has led to the apparently paradoxical result of raising the mountains.

Alluvial Fans and Cones

Many youthful mountain ranges, block mountains, and plateaus descend steeply to the neighbouring lowlands; generally, but not in all cases, because they are bounded by eroded fault-scarps. Where a heavily laden stream, flowing swiftly through a ravine or canyon, emerges at the base of such a slope, its velocity is suddenly checked by the abrupt change of gradient and a large part of its load of sediment is therefore dropped. The obstructed stream—as in delta formation—divides into branching distributaries, and the heap of debris spreads out as an *alluvial fan*. If the circumstances are such—arid or semi-arid conditions are specially favourable—that most of the water sinks into the porous deposit, practically the whole of the load is dropped and the structure rapidly gains height and becomes an *alluvial cone*. There are, of course, all gradations from steep-sided cones of coarse debris, through fans of moderate inclination, to widespread sloping sheets of fine alluvium. Where closely spaced streams discharge from a mountainous area across a *piedmont* (a mountain-foot lowland), their deposits coalesce to form a *piedmont alluvial plain.*

All these features are well displayed in Western America : along the eastern base of the Rockies, where the Front Range faces the Great Plains ; along the eastern edge of the Sierra Nevada, where the eroded fault scarp slopes down to the Great Basin ; and in many other similar situations on the flanks of the block mountains of the Great Basin (Fig. 104). They are also developed on a large scale at the foot of the

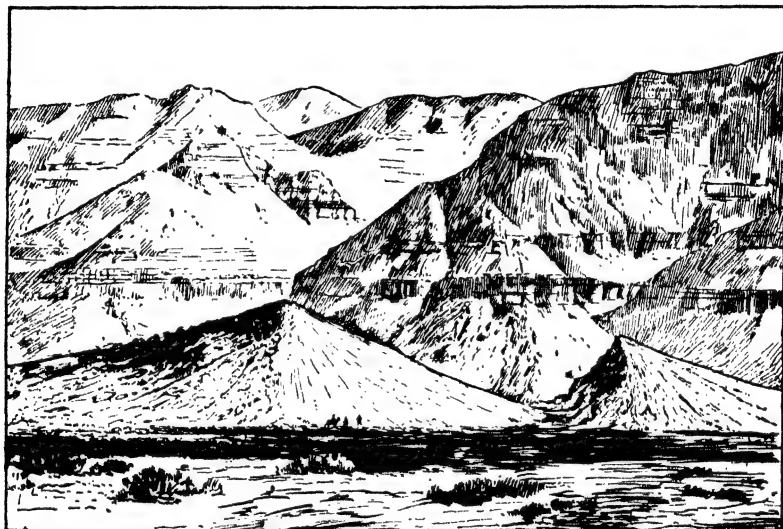



Fig. 104
Alluvial cones at the mouths of canyons in southern Utah
(*After U.S. Geol. Survey*)

Himalayas and the Andes. A familiar Alpine example of an alluvial fan of gentle slope is the one between Lake Thun and Lake Brienz on which Interlaken is built. Here a stream coming down from the Jungfrau has built a fan across what was originally a single lake, so dividing it into two. In all the localities mentioned above there are many examples of river deflection due to the growth across the channel of alluvial fans deposited by tributaries.

SUGGESTIONS FOR FURTHER READING

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The following general works apply also to many of the later chapters :

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Chapter XII

GLACIERS AND GLACIATION

Snow Fields and the Maintenance of Glaciers

Glaciers are masses of ice which, under the influence of gravity, flow out from the snow fields where they originate. Permanent snow fields occur in every continent except Australia. The level up to which the snow melts in summer, *i.e.* the lower edge of a permanent snow field (if present), is called the *snow line*. Its height varies with latitude from sea level in the polar regions to 2,000 feet in S. Greenland and S. Chile, 5,000 feet in S. Norway and S. Alaska, 9,000 feet in the Alps, 13,000 – 16,000 feet in the Himalayas, and 17,000 – 18,000 feet on the high equatorial peaks of Africa (Plate 45) and the Andes. It is of interest to notice that the higher summits of the Scottish Highlands, *e.g.* Ben Nevis, just fail to reach the level of the snow line as it would be in Scotland.

Low temperature alone is not sufficient to ensure the growth of a snow field. Although northern Siberia includes one of the coldest regions of the globe, and has permanently frozen soils from Novaya Zemlya to Bering Strait, it is kept free from perpetual snow because the scanty winter falls are quickly dissipated in the spring. Snow fields are formed and maintained where the winter snowfall is so heavy that summer melting and evaporation fail to remove it all. Snow may also be swept away by the wind, or lost from steep slopes by avalanching. The most favourable situations are therefore gentle slopes and hollows shaded from the sun and sheltered from the wind. A balance of the snowfall is then left over to accumulate from year to year, and the snow field grows in depth and surface area until pressure on the ice which is formed in depth is sufficient to start its outward flowage as a glacier.

The loose feathery snow that first gathers in the collecting grounds gradually passes into a closely packed form—the *névé*

of the Alpine snow banks—retaining a white colour because of the presence of entangled air. As the snow crystals are buried and compacted, the air between them is squeezed out, water from melting snow seeps in and freezes, and so the deeper layers are transformed into compact, but still porous ice. The clear blue bands often seen in the exposed flanks of glaciers differ from the opaque white ice in being free from bubbles of air. Glacier ice in bulk is a granular aggregate of interlocking grains, each grain being an individual crystal of ice.

Glaciers originating in valley heads creep slowly downwards as tongue-like streams of ice, flowage being maintained by the yearly replenishment of the névé fields. Ultimately the glaciers dwindle away by melting and evaporation, their fronts or *snouts* reaching a position—which may be thousands of feet below the snow line—where the forward movement of the ice is just balanced by the wastage. In response to seasons of heavy snowfall whereby the supply is increased, or of low temperature whereby the wastage is reduced, the glacier extends farther down the valley, and the snout then becomes steep. Conversely, in response to a falling off in the rate of supply or to an increased rate of wastage the snout tapers (as seen in Plates 5B and 48) and recedes up the valley. During the present century the fronts of many glaciers are known to have retreated, though previously they had been slowly advancing for many years.

The capacity of powerful valley glaciers to reach low levels before they melt away is due not only to the immense supplies of ice which are drained from the uplands, but also to the fact that the area exposed to wastage is small compared with the volume of the ice. Because the glacier is very viscous, and therefore moves extremely slowly, it occupies its valley to a very great depth. To drain a given area the cross section of a glacier has to be enormously greater than that of the corresponding river, and in accordance with this comparison the streams that suffice to carry off the summer melt-water from the snout of a glacier always appear small and insignificant (Plate 48).

When glaciers overflow the land and terminate in sea-

water sufficiently deep to allow the ice to float, huge masses break away from the front and become *icebergs*. Theoretically about nine-tenths of an iceberg would be submerged if it were made of pure ice. The actual proportion, however, is subject to variation according to the proportion of entangled air and the load of rock debris present in the ice. Some of the vast tabular icebergs liberated from the front of the Antarctic ice float with as much as one sixth of their total height above the sea.

Types of Glaciers

Glaciers fall naturally into three main classes :

(*a*) *Ice sheets* and *ice caps* that overspread continental or plateau regions of supply, where the snow line is low, creeping with a slow massive movement towards the margins.

(*b*) *Mountain* or *valley glaciers* occupying the pre-existing valleys of mountain ranges that rise above the snow line.

(*c*) *Piedmont glaciers*, consisting of sheets of ice formed by the coalescence of several valley glaciers which have spread out below the snow line—like lakes of ice—over a lowland area of wastage. Certain gradational and subsidiary types also occur, and are referred to below.

Greenland and Antarctica provide the only examples of *continental ice sheets* that still exist. There is, however, overwhelming evidence that 25,000 to 30,000 years ago immense ice-sheets of similar character covered half of North America and most of north-western Europe. The Greenland ice-sheet, about half a million square miles in extent, is largely enclosed within a mountainous rim. Near the middle of the sheet the ice has been shown by seismic methods (page 371) to be over 8,000 feet thick, indicating that the elevation of the actual rock floor is only about 1,600 feet. Towards the edge the higher peaks and ridges of the mountains project through the ice as *nunataks*. The ice itself overflows through passes in the mountain zone and feeds the valley glaciers of the valleys leading down to the coast.

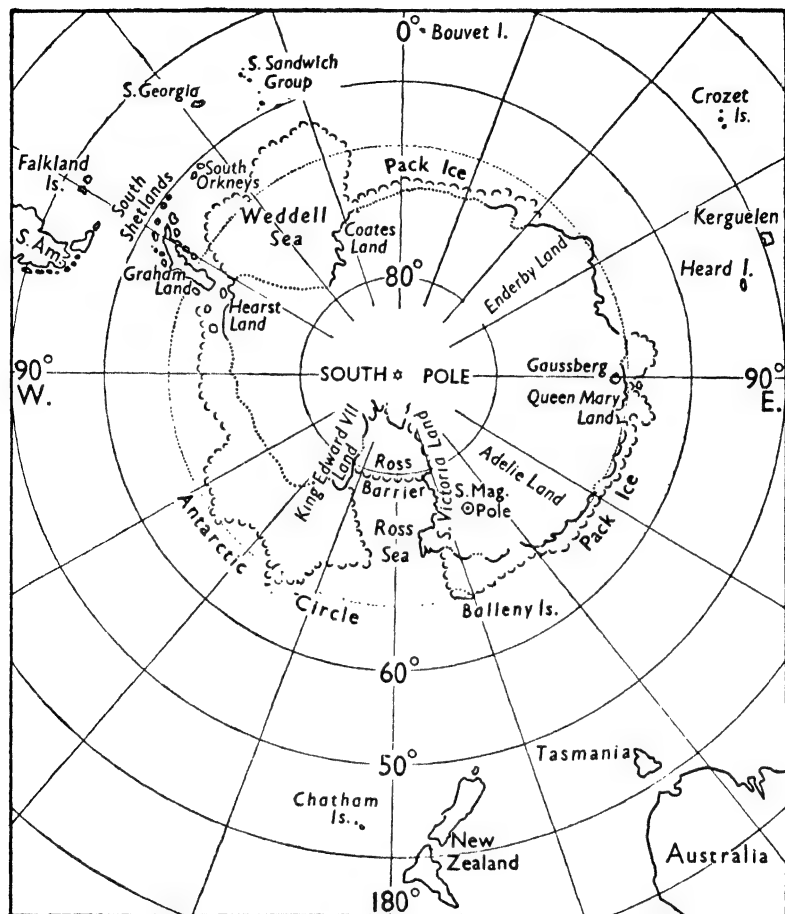



Fig. 105
Map of Antarctica

The ice sheet of Antarctica, seven times as extensive as that of Greenland, forms a great plateau rising to over 9,000 feet (Fig. 105). Except in a few localities of fringing mountains, where there are marginal glaciers and a coastal strip, the ice sheet overruns the coast and spreads over the ocean as vast floating masses of shelf ice. The best known of these is the Great Ross Barrier, which terminates in sheer cliffs of floating

[*E.N.A.*

FIG. 106

A view of the Malaspina Glacier with snow-clad mountains of Alaska in the background

ice rising 100 to 160 feet above the Ross Sea. The Barrier ice is worn away by submarine thawing, marine erosion, and the breaking off of gigantic tabular icebergs. Wastage is slowly overtaking supply, for the high walls of the Barrier have receded many miles to the south since Ross first discovered them in 1841.

Smaller ice-sheets, distinguished as *plateau glaciers* or *ice caps*, cover large areas in Iceland and Spitsbergen, from which they emerge through marginal depressions as blunt lobes or large valley glaciers. The tips of the underlying mountains project from certain less continuous caps of highland ice. Where the supply of ice is rather less, these pass into a network of connected glacier systems, the ice of each valley system overflowing the cols into neighbouring valleys and smothering all the lower divides. Such gradational types, well represented in Spitsbergen, lead to the more familiar valley glaciers.

Trunk glaciers and the tributary valley glaciers feeding

[*G. P. Abraham, Ltd., Keswick*

(A) The Mer de Glace, France

[*U.S. Geol. Survey*

(B) Aerial view of the Nabesna Glacier, Alaska

VALLEY GLACIERS

[*F. N. Ashcroft*

The Rhône Glacier, showing crevasses, viewed from the ridge above the Belvedere Hotel, near Gletsch, Switzerland

into them occupy the upper parts or the whole of the valley system of a single drainage area (Plate 46). Smaller valley glaciers, with few tributaries or none, are confined to single valleys. Valley glaciers—apart from those draining ice-sheets and caps—characteristically originate in deep arm-chair-shaped hollows, called *corries* or *cirques*, situated at the valley heads (see Plate 47). Small isolated glaciers occupying hanging valleys (page 221) or subsidiary corries perched high on the side of a deeper valley are referred to as *hanging glaciers* (tongue-shaped) or *corrie glaciers* (horseshoe-shaped).

Where a glacier passes from a restricted channel to a more open lowland, it fans out into an *expanded foot*, and where several neighbouring glaciers so emerge a *piedmont glacier* results. The outstanding example of the latter type is the great Malaspina Glacier of Alaska (Fig. 106). Maintained by the confluence of the glaciers from Mt. St. Elias and the neighbourhood of the Canadian frontier, it has an area of about 1,500 square miles, and locally reaches the sea. As a result of surface melting, much of the outer margin is thickly covered with morainic debris and soil which here and there support dense forests of pine.

The Movement of Glaciers

Were it not for the fact that ice in bulk can flow, the world would now present a very different appearance. Practically all the water of the oceans would be locked up in gigantic circum-polar ice fields of enormous thickness. The lands of the tropical belts would be deserts of sand and rock, and the ocean floors vast plains of salt. Life would survive only around the margins of the ice fields and in rare oases fed by juvenile water.

The most rapidly moving glaciers are those of Greenland, some of which advance as much as 60 feet a day in the summer. In general, however, a few feet a day is a more characteristic rate. The Mer de Glace (Plate 46A) barely exceeds two feet a day, and the Beardmore Glacier of Antarctica, the greatest in the world, moves at less than three feet a day.

By observing the changes in position of lines of stakes driven into the ice it is found that the middle of a glacier moves more rapidly than the sides, and that there is a similar decrease in velocity near the floor. The rate of flow increases with the steepness of the slope, with the thickness and temperature of the ice, and with constriction of the valley sides. Movement is retarded by the presence in the ice of a heavy load of debris and by friction against the rocky channel. These facts suggest that the flowage of glaciers—a remarkable phenomenon that calls for a brief explanation—is controlled mainly by stress differences and temperature.

The liberation of molecules of water from ice by a rise of temperature is a familiar process. It is also well known that uniform pressure lowers the melting point of ice, and thus stimulates its transformation into water. More important, however, is the fact that non-uniform pressure or stress is many times more effective in liberating molecules of water from rigid grains of ice. The mechanism of skating provides the key to the problem of glacier flow. A skater really glides in a narrow groove of water formed momentarily under the intense stress applied to the ice by the thin blades of his skates. As he passes, the water immediately freezes again.

The interlocking crystal grains within a sloping mass of ice are subjected to stresses which vary from point to point, and wherever the strain is most severe, mobile molecules and microscopic films of water are liberated. These act as a lubricant and facilitate minute movements of the grains among themselves. As one grain is pressed against another water diffuses along intergranular boundaries into places of lower stress, and there freezes on to the grains with which it is in contact. Slipping along fracture planes in individual grains also contributes to the movement. Since the pressure gradient is down the valley, there is a constant migration of material from grain to grain in that direction. The whole mass thus flows by a process of re-crystallization which is closely akin to that involved in the metamorphism of ordinary rocks. The agents of metamorphism are high temperature, stress differences, and migrating fluids. In the interior of a glacier the

temperature is already very " high " in the sense that the ice is near its melting point ; stress is provided by the weight of overlying and upstream ice ; and the migrating fluid is water.

A glacier has an outer crust of ice, averaging perhaps about 200 feet in thickness, in which the stress differences are insufficient to promote flowage. This rigid crust is carried along, and friction against the sides and floor is also overcome, by the movement of the deeper parts. Where the movement is retarded or stopped by a load of debris, as often happens near the snout of a glacier, the stagnant ice is over-ridden by clean, mobile ice along well-marked thrust planes.

Surface Features of Glaciers

Crevasses.—Within limits controlled by the processes of ice flowage a glacier can accommodate itself to its channel. Where the ice passes through a constriction in a valley it thickens, and the rigid crust is thrown by lateral compression into wave-like *pressure-ridges.* On the other hand, where the valley opens out, or where a glacier passes over a declivity or round a bend, or fans out into an expanded foot, the ice is stretched and cracked into a series of deep gaping *crevasses.* These may be hidden by snow bridges, and the treacherous surface then becomes very dangerous to cross.

Transverse crevasses develop across a glacier wherever there is a marked steepening of the slope of its floor (Fig 108). *Longitudinal* crevasses, roughly parallel to the direction of flowage, are formed wherever ice is obliged to spread out. *Marginal* crevasses (Plate 47), pointing upstream from the sides of the glacier, develop as shown in Fig. 107. Because of the higher velocity towards the middle, a line AB is later extended to A′ B′, and the resulting tension cracks the ice at right angles to A′ B′. When two or more sets of crevasses intersect, the surface of the glacier is torn into a broken mass of jagged ice pinnacles known as *seracs.* Near the top of the névé field of a corrie a very wide and deep crevasse, called the *bergschrund,* opens in summer where the head of the glacier

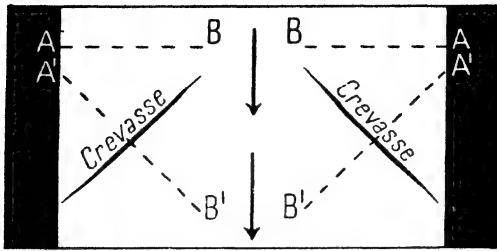



Fig. 107
Diagram to show the development of marginal crevasses as a result of differential ice flowage

pulls away from the ice and snow adhering to the precipitous walls (Fig. 108). It often happens that several such fissures are formed instead of an especially large one (Fig. 109).

Moraines.—Rock fragments liberated from the steep slopes above a glacier, mainly by frost shattering, tumble down on the ice and are carried away. Thus the sides of a glacier

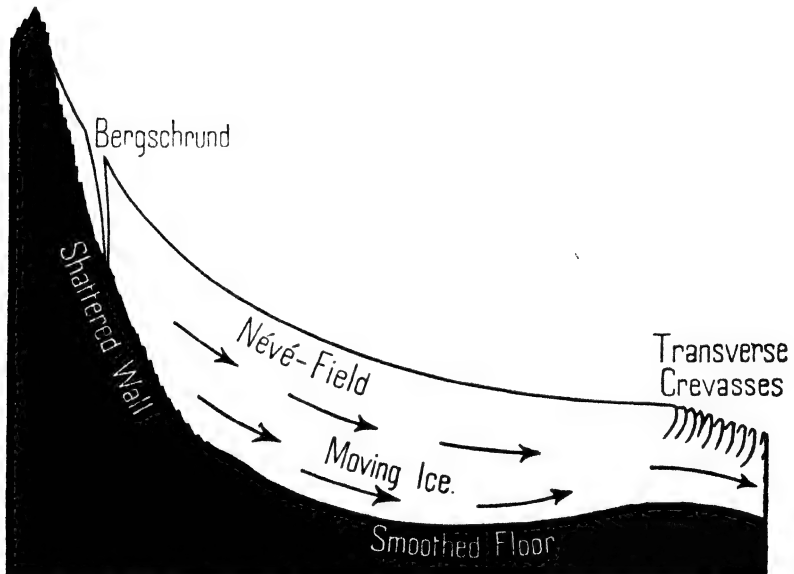



Fig. 108
Schematic section through a corrie occupied by the head of a glacier, showing the bergschrund near the top and transverse crevasses above the threshold

[*F. N. Ashcroft*

Ice cave and source of the Rhône, snout of the Rhône Glacier, near Gletsch, Switzerland

[H.M. Geol. Survey

(A) Striated surface of slates, Kilchiaran, Islay

 [H.M. Geol. Survey

(B) *Roche moutonnée* of schist with evidence of plucking in front, Glen Nevis, Inverness-shire

become streaked with long ribbons of debris described as *lateral moraines*. When two glaciers from adjacent valleys coalesce, the inner moraines of each unite and form a *medial moraine* on the surface of the united glacier (Plate 46B). A trunk glacier fed by many tributaries may thus come to be ridged with a series of medial moraines composed of materials from different parts of the area of supply, thus providing samples of rocks that might otherwise be unobtainable.

Sooner or later part of the debris is engulfed by or washed

FIG. 109

Sketch of bergschrund crevasses in an ice-filled corrie at the head of a glacier (*From an aerial photograph of the Gelmerhorner, Switzerland*)

into crevasses. Material that is enclosed within the ice is referred to as *englacial moraine*. A certain proportion reaches the sole of the glacier, and there, together with the material plucked or scraped from the rocky floor, it constitutes *subglacial moraine*.

If the lower part of the ice becomes so heavily charged with debris that it cannot transport it all, the excess is deposited as *ground moraine*, which is then over-ridden by the more active ice above. All the varied debris, ranging from angular blocks and boulders to the finest ground-down rock flour, that finally arrives at the terminus of the glacier is dumped down when

the ice melts. If the ice front remains stationary for several years an arcuate ridge is built up, called a *terminal* or *end moraine*. If, however, the snout is retreating summer after summer, no piling up of a ridge is possible. The load liberated from the receding front then forms an irregular sheet which rests on the ground moraine already deposited.

Melting and Drainage.—Thin isolated slabs of rock or patches of debris on the surface may be sufficiently heated by the sun to melt the underlying ice. Larger blocks, however, act as a protection from the sun's rays, and as the surrounding ice melts away they are left as *glacier tables* perched on a column of ice. Even morainic ridges may stand out for a time on thick walls of ice.

In sunny weather small pools and rills diversify the surface, gathering into streams which mostly fall into crevasses. By a combination of melting and pot-hole action (aided by sand and boulders) deep cauldrons called *glacier mills* or *moulins* are worn through the fissured ice, and the water may escape to the snout through a tunnel. There, with melt-water draining down the tapering end, it begins to flow down the valley as a milky stream laden with fine particles (Plate 48).

Glacial Erosion

As we have seen, a glacier soon acquires a load of morainic material. Moreover, loose debris on the floor and sides is quickly dislodged and engulfed by actively advancing ice. Blocks from protuberances of jointed bedrocks are sheared off and withdrawn from the down-stream and unsupported side by a quarrying process referred to as *plucking*. The ice works its way into joints, bedding planes, and other fractures and closes round projecting masses with a firm grip, so that block after block is torn out of position and carried away. The ragged surface left behind is readily susceptible to further plucking, and the process continues until the obstruction is removed or the glacier wanes.

Thus, even pure ice, which by itself would be a very ineffective tool for eroding massive rocks, is sooner or later trans-

formed into a gigantic flexible file with embedded fragments of rock for teeth. *Abrasion* is the scraping and scratching of rock surfaces by debris frozen into the sole of a glacier or ice sheet. The larger fragments cut into and groove the floor and sides, and are themselves worn flat and striated. The finer materials act like sandpaper, smoothing and polishing the rock surfaces and producing more powdered rock, or *rock flour*, in the process.

The rate of glacial erosion is extremely variable. Theoretically, the rate of abrasion is approximately proportional to the cube of the velocity of the ice against its channel. Thus a powerful glacier in northern Greenland may be 30,000 times more effective than the sluggish glaciers of the Alps. A continental ice sheet moves so slowly that it cannot be expected to do much more than remove the soil and smooth-off the minor irregularities of the buried landscape. In such a case the broader features of the pre-glacial relief are, on the whole, protected from denudation, though the surface is modified in detail into a characteristically hummocky form of knobs and hollows which reflect the varying resistances offered by the rocks to abrasion. But when the outflowing ice, or a valley glacier in a mountain district, is concentrated in a steeply descending valley, the erosive power reaches its maximum, and the pre-glacial relief is strongly accentuated. Beyond the region of steep gradients and rapid movement the rate of erosion gradually falls off and gives place to deposition as the ice becomes overloaded and reaches the zone of wastage. The three realms of supply, movement, and wastage are clearly seen in Plate 46B.

The geological work accomplished by ice, including erosion and deposition and the resulting effects of these processes on the surface, is collectively known as *glaciation*. The sculpturing of the surface beneath existing glaciers can be studied directly only in a limited way, by exploring ice caves and descending crevasses. Much more can be learned by taking advantage of the fact that many glaciers have receded up their valleys in recent years. Throughout the historical period there have been periodic fluctuations in the volume and extent of glaciers, but without any indication of cumulative waxing or waning.

[*C. E. Wegmann*

Fig. 110

Ice-moulded surface of *roche moutonnée* type, Sitterskar, Soderskar Archipelago, south coast of Finland

Thousands of years ago, however, the glaciers were enormously greater than their shrunken descendants of to-day. One of the earliest observers to suspect that glaciation was formerly far more extensive was de Saussure, the first scientific explorer of the Alps. In 1760 he noticed that miles below the snouts of the Alpine glaciers the rock surfaces were scratched and smoothed—in striking contrast with the frost-splintered peaks above—and strewn with morainic material exactly like that still being carried and deposited by the ice. He rightly concluded that the glaciers had formerly extended many miles beyond their then limits. But the "glacial theory" met with scant approval until after 1840, when the great naturalist Louis Agassiz awakened more general interest in the subject by the publication of his classic studies on the glaciation of the Alps. In later years Agassiz recognised that the similarly striated rock surfaces and morainic deposits of Scotland were also due to the former passage of ice. With a wealth of irre-

sistible evidence he convinced the scientific world that such features could be accounted for in no other way. It is now familiar knowledge that the landscapes of vast areas of Europe and North America bear the unmistakable hall-marks of glaciation. Thus it happens that in many countries the characteristic effects of ice erosion and deposition, modified but little by subsequent weathering and river action, can be seen and studied close at hand.

Among the evidences of erosion by continental and valley glaciers, striated surfaces (Plate 49A) and ice-moulded hummocks of the more resistant bedrocks (Fig. 110) are of widespread occurrence. The residual hummocks vary widely in size, and have a characteristically stream-lined form which is

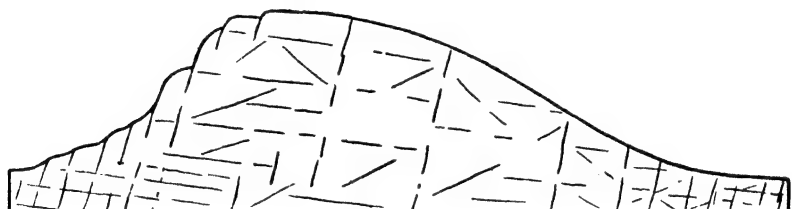



Fig. 111

Section across a typical *roche moutonnée*, showing the effect of ice abrasion where the rock is sparsely jointed, and of plucking where jointing is well developed

related to the direction of ice movement. The side up which the ice advanced rises as a smoothly abraded slope, while the lee side falls more steeply, sometimes as an abraded slope, but often by a step-like series of crags and ledges obviously due to the plucking out of joint blocks (Fig. 111 and Plate 49B). Seen from a distance the more isolated examples resemble sheep lying down, or wigs placed "face" downwards. They are, therefore, described as *roches moutonnées*, a term first used by de Saussure in 1804 in reference to the sheep-skin wigs, styled *moutonnées*, which were then in vogue.

Highly resistant obstructions, such as old volcanic plugs, that lay in the path of the ice, like protruding knots in a plank of wood, are responsible for an erosional feature known as *crag and tail* (Fig. 112). The *crag* boldly faces the direction

from which the ice came, while the *tail* (bedrock with or without a covering of boulder clay) is a gentle slope on the sheltered side, where the softer sediments were protected by the obstruction from the full rigour of ice erosion. A classic example is provided by the Castle Rock of Edinburgh, from the eastern side of which the High Street follows the sloping crest of the tail. The massive basalt plug diverted the ice-flow, and deep channels, now occupied by Princes Street

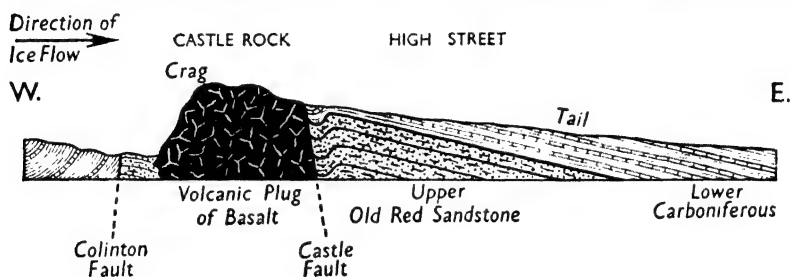



Fig. 112
Crag and Tail, Edinburgh

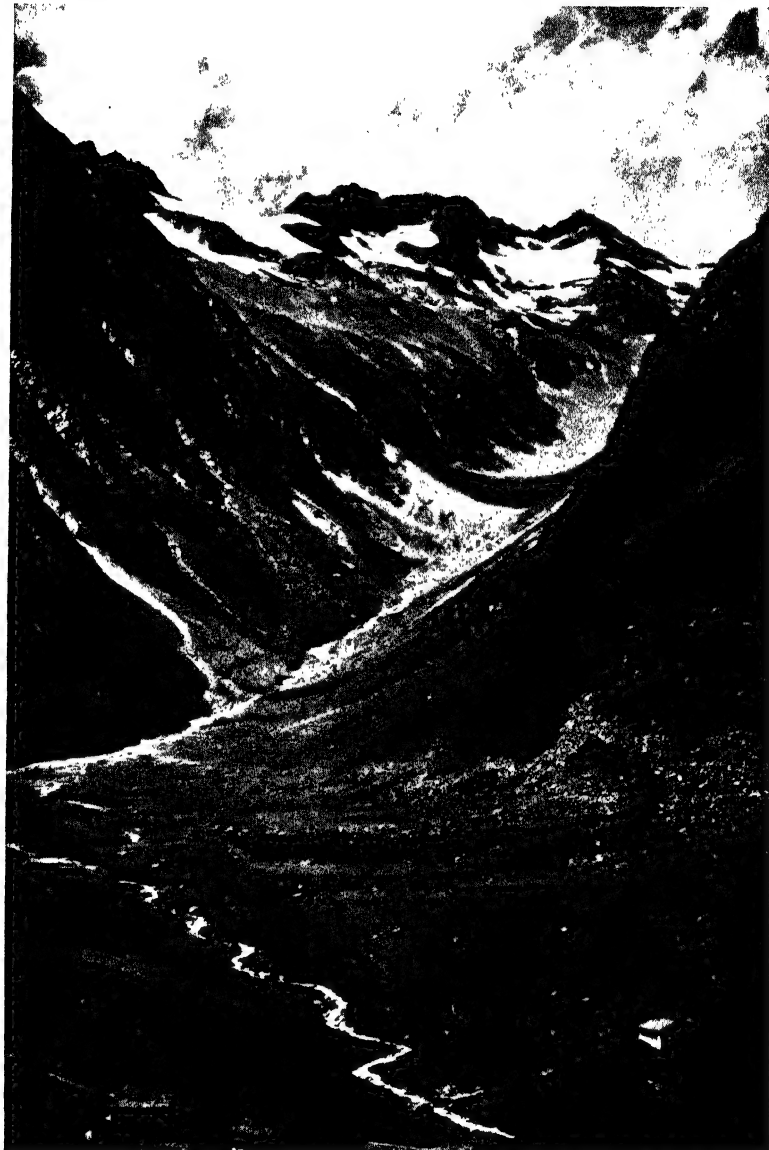
Gardens and the Grassmarket, were excavated in the sediments on each side of the crag and tail feature.

In mountainous and upland coastal regions with well developed valley systems the topographic modifications superimposed on the landscape by glacial erosion include U-shaped valleys with truncated spurs and hanging tributary valleys; corries or cirques surmounted by sharp-edged ridges and pyramidal peaks; and rock basins and fjords. Waterfalls descending the precipitous valley sides, and lakes occupying the overdeepened hollows of the valley floors, add variety to an assemblage of features that can be easily distinguished from those of unglaciated regions.

Corries and Associated Features

It has been observed that chance hollows occupied by persistent snowbanks are steadily cut back and deepened by (*a*) disintegration of the marginal and underlying rocks by frost

[G. P. Abraham, Ltd., Keswick

The Matterhorn, Switzerland

[*F. N. Ashcroft*

U-shaped glaciated valley. Val Giuf (tributary of the Upper Rhine) viewed from the slopes near the châlets of Milez, Switzerland. Granite of the Aar Massif in the middle distance

and thaw, and (*b*) removal of the shattered debris by falling, avalanching, and transport by melt-water. By this process of snow-patch erosion or *nivation* the slopes above are undercut and the surrounding walls are kept steep as they recede (Fig. 113). The larger hollows grow more rapidly than the smaller ones, especially near and above the snow line, until the mountain slopes and valley sides are festooned with deep snowfields, the largest of all being at the valley heads. Eventually these nourish small glaciers which carry away the debris and begin more active excavation of the floor. Headward erosion of the walls continues, not only by frost sapping at the exposed edges of the snowfield, but also by a process of subglacial disintegration which comes into play whenever the

[*F. Nansen*

FIG. 113

Corries developed by snow rotting on the cliffs of Spitsbergen

bergschrund allows surface water to reach the rocks behind or beneath the ice. Draining into cracks and joints, the water freezes and breaks up the rocks until they are gripped by the ice, and carried away as ground moraine. Thus by the cooperation of several processes the great amphitheatres known as corries or cirques are eventually hollowed out (Figs. 108 and 116).

During the stage of most intense glaciation the floor of a growing corrie is subjected to especially vigorous scouring in consequence of the great thickness and high pressure of the ice and snow above it. A shallow rock basin may then be excavated by the outflowing ice, to become the site of a mountain tarn or lake after the ice has disappeared (Plate 54B). Such lakes may also be held back by arcuate ridges of morainic

material left stranded by the waning ice during its final recession.

Two adjoining corries may approach and intersect until only a sharp-edged dividing wall remains between them. The resulting precipitous ridge is known as an *arête.* When the ice has gone the steep rocky slopes fall a ready prey to frost action, and soon become aproned with screes. Many an upland region has been eaten into by corrie erosion from several sides at once, and so reduced to a series of arêtes radiating like a starfish from a central summit. Snowdon and Helvellyn are good examples. At a later stage the arêtes themselves are worn down, and the central mass, where the heads of three or more corries come together, remains isolated as a conspicuous pyramidal peak. In this way the *horns* of the Alps have been formed, the world-famous Matterhorn being the type example of its class (Plate 50).

Modifications of Valleys by Glacial Erosion

By the passage of a vigorous glacier through a pre-existing river valley the mantle of rock-waste is removed, the overlapping spurs are trimmed off and ground into facets, and the floor is worn down. The valley is thus widened and deepened, and is eventually remodelled into a U-shaped trough with a broad floor and steep sides and a notable freedom from bends of small radius (Plate 51). Flat floors are not uncommon, however, where the bottom of the trough has been levelled up by subsequent deposition of alluvium. Whole valley systems may have been completely overwhelmed by ice-sheets, but in less severely glaciated regions, where valleys have not been entirely filled by ice, the upper slopes may remain as high-level benches which meet the ice-steepened walls in a prominent shoulder (Plate 51). The cross profile is like a U sunk in a V.

Tributary valleys have their lower ends cut clean away as the spurs between them are ground back and truncated (Fig. 114). The floor of a trunk glacier, moreover, is deepened more effectively than that of a weak lateral feeder. Thus, after

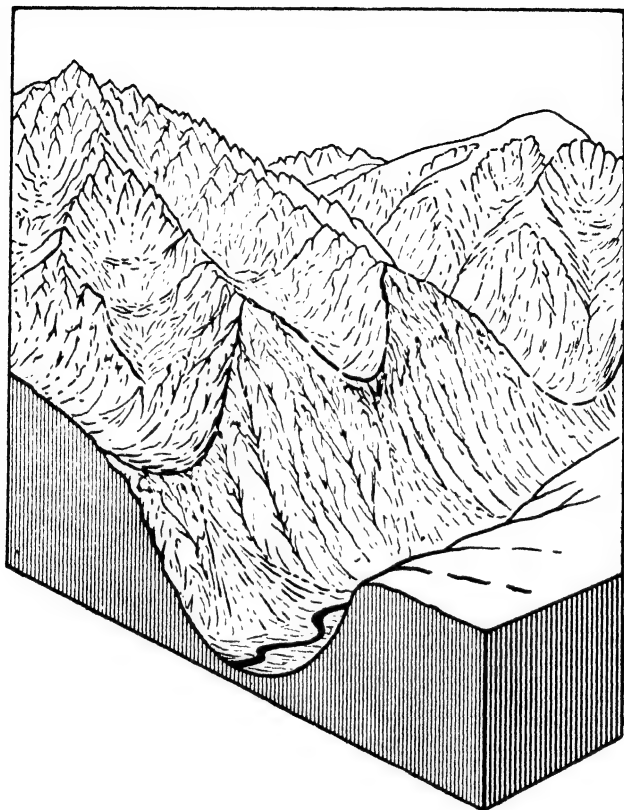



Fig. 114

Block diagram illustrating some of the characteristic landscape features of glaciated valleys and mountains : U-shaped valley ; truncated spurs ; hanging tributary valleys ; corries, arêtes, and horns. The summit of the hill on the right and the bench across the lower right-hand corner are depicted as they would be if they had remained unglaciated. (*Modified after W. M. Davis*)

a period of prolonged glaciation the side valleys are left hanging high up on the flanks of the main trough. The streams from such *hanging valleys* plunge over their discordant lips in cascades or waterfalls, some of which are amongst the highest in the world. The Yosemite Valley in the Sierra Nevada of California is renowned for its impressive examples of these and other spectacular features due to glacial erosion (Plates

52 and 53). A remarkably similar glacial trough—the finest of its kind in Europe—is the Lauterbrunnen valley, with its celebrated Falls, between Interlaken and the Jungfrau.

Glacially excavated floors are deepened very unevenly, the effect at each point depending on the thickness and velocity of the ice and the nature and structure of the bedrocks. Poorly consolidated strata are scoured out more rapidly than resistant rocks, and tracts of well-jointed rocks are selectively quarried away by plucking. Thus, where the ice encounters a sequence of rocks of varied resistance the floor is excavated into a series of successive steps, often with abrupt descents from one tread

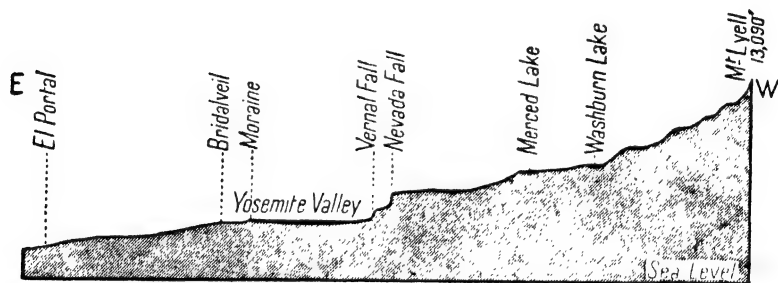



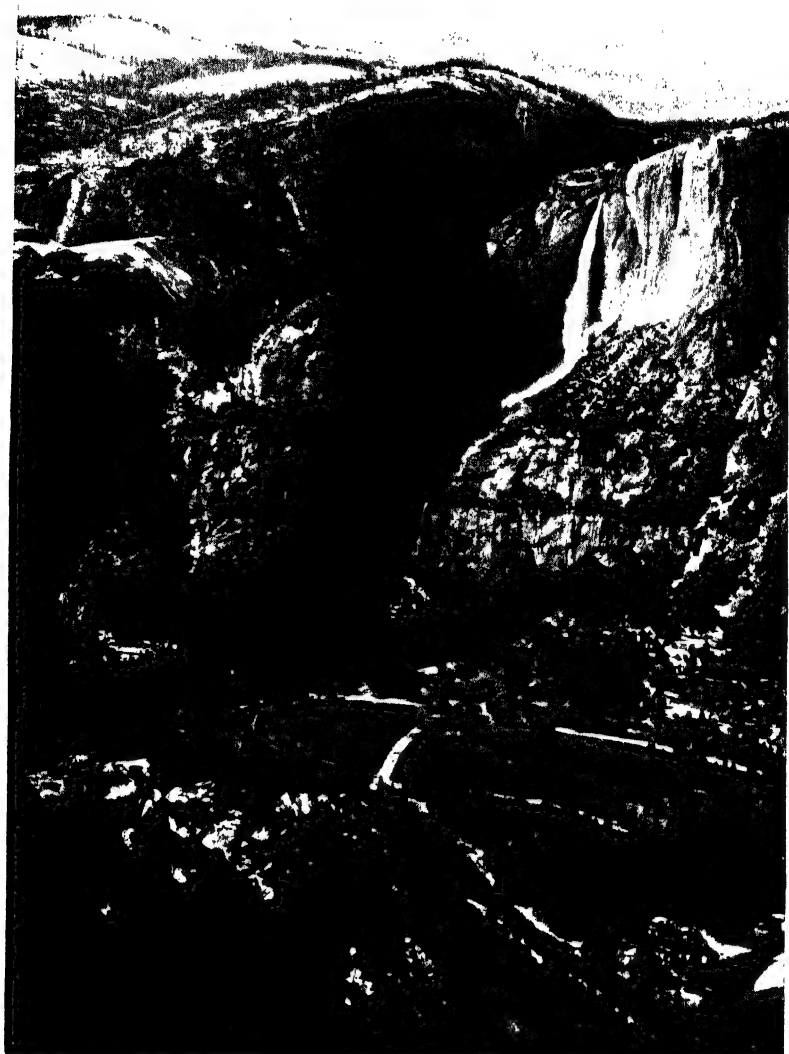
Fig. 115

Longitudinal profile along the Yosemite Valley (see Fig. 184 for locality). A typical "glacial stairway" developed by selective ice erosion
Length of section = 36 miles

to the next (Fig. 115). A comparable effect due to varying ice thickness is seen where a trunk glacier has been fed from a cluster of corrie glaciers around the valley head. Below the confluence the suddenly increased erosive power is witnessed by a correspondingly sudden drop from the corrie mouths to the floor of the glacial trough (Fig. 116). "Trough-end" walls of this kind are magnificently developed at the heads of the Lauterbrunnen and Zermatt valleys.

Thus it happens that the long profile of a glaciated valley may resemble a giant stairway. The treads may even be hollowed into basins with a barrier of resistant rock in front. Such rock basins are now occupied by lakes of various lengths and depths, or by tracts of alluvium representing the sites of

Truncated spur of El Capitan — Half Dome — Cathedral Rocks, Hanging Valley and Bridalveil Falls

Yosemite Valley, Sierra Nevada, California (see Fig. 115)
(R. H. Anderson, U.S. National Park Survey)

[*R. H. Anderson, U.S. National Park Service*

Yosemite Falls, Yosemite Valley, Sierra Nevada, California

former lakes which were so shallow that they have since been silted up. Though referred to as " basins," these depressions are generally greatly elongated, and some of them have been excavated to depths well below sea level. It has been objected that the ice at the bottom of a basin could not flow out of it,

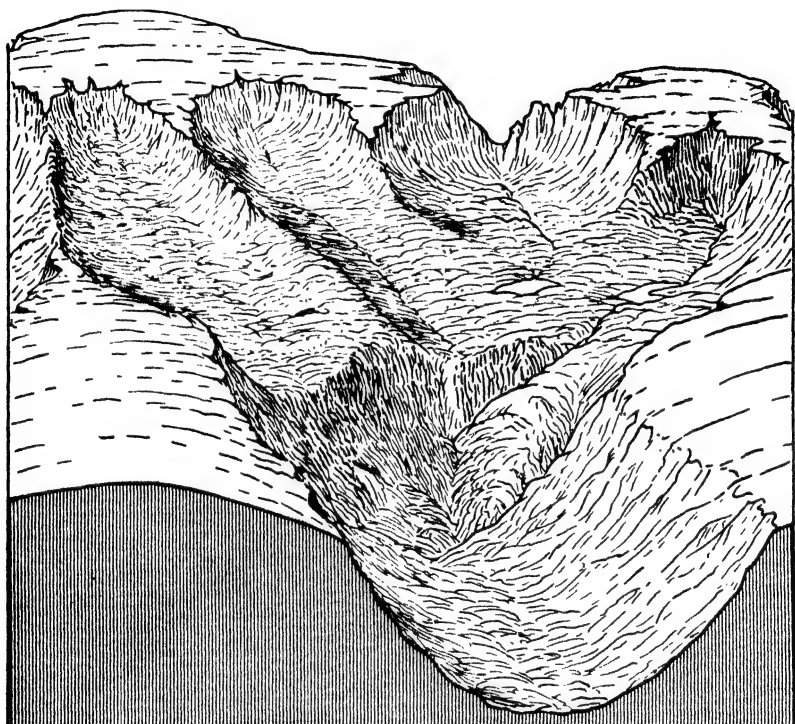



FIG. 116

Block diagram to illustrate the " trough-end " rock step at the head of a glaciated valley fed by several confluent corries. (*Modified after W. M. Davies*)

that is, up the slope at the lower end. However, in the appropriate circumstances, this objection is not well founded. Ice can move upslope provided that it has a means of exit, and is moving from a place of high pressure to a place of low pressure. The condition for flow is that the *surface* of the ice should have a downward gradient sufficiently steep to maintain the re-

quisite head of pressure. The following are examples of lakes which occupy conspicuously overdeepened basins and troughs.

Lake	*Maximum depth (in feet)*	*Height of surface above sea level*	*Maximum depth of floor below sea level*
LAKE DISTRICT			
Windermere *	219	128	91
Wastwater *	258	200	58
SCOTLAND			
Loch Coruisk, (Plate 54A)	125	25	100
Loch Lomond *	653	20	633
Loch Ness	754	53	701
Loch Morar	1,017	30	987
SWISS-ITALIAN ALPS			
L. Maggiore	1,220	636	584
L. Como	1,345	650	695

* Morainic deposits on the terminal bedrock barrier add slightly to the depth of these lakes. See Fig. 118 for an example of such a double barrier.

Fjords are greatly overdeepened glacial troughs that reach the coast below sea level, so that, instead of forming elongated lake basins, they have become long arms of the sea stretching inland between steep rocky walls. The terminal rock barrier (with or without a cover of moraine) occurs near the seaward entrance, and is usually submerged at a shallow depth. This is the *threshold* of the fjord. Along the west coast of Scotland gradations from the exposed barriers of the freshwater lochs to the submerged thresholds of the fjords (sea lochs) are well illustrated. The terminal rim of Loch Morar is within a very short distance of the sea, and is only 30 feet high. The thresholds of Lochs Etive and Leven are lower, but are uncovered at low tide. Twenty-three of the remaining sea lochs have permanently submerged thresholds near their entrances.

Fjords have been developed during the intense glaciation of dissected coastal plateaus and mountains of appropriate structure in countries such as Scotland, Norway, Greenland, Labrador, British Columbia, Alaska, Patagonia, and New Zealand. In plan (Fig. 117) they everywhere have a characteristic rectilinear pattern which is clearly determined by the distribution of belts of structural weakness. The latter may be synclines of relatively weak sediments or schists enclosed by massive crystalline rocks (as in the Sogne and Har-

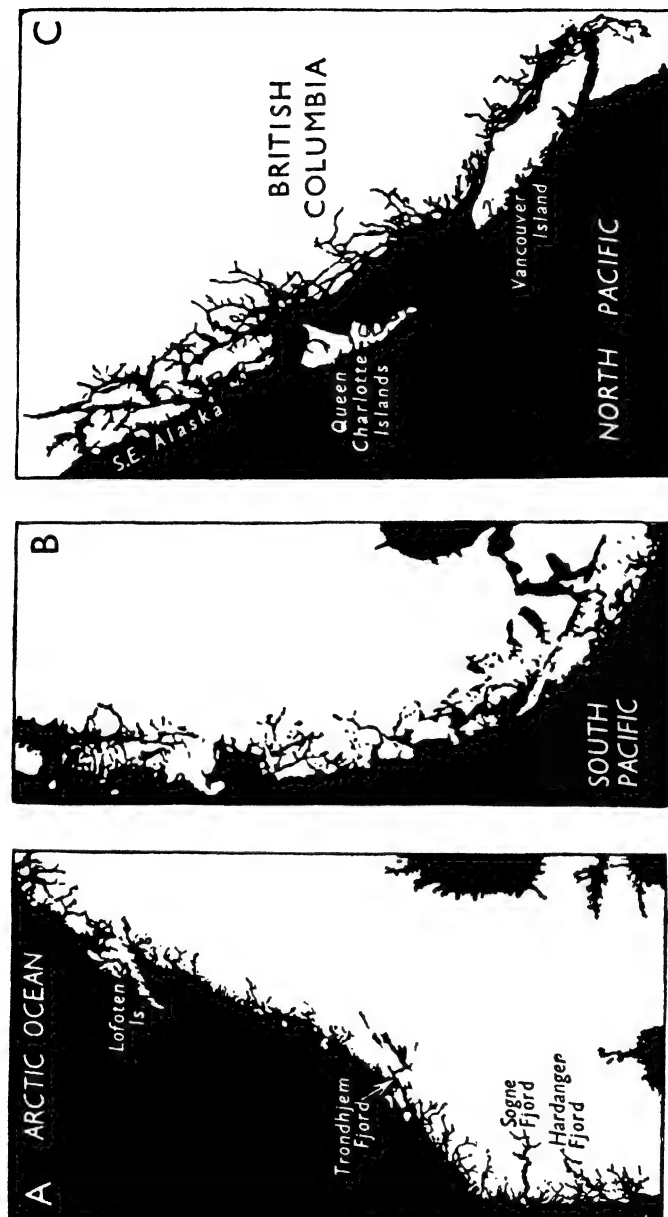



Fig. 117

Three examples of fjord coasts

(A) Norway (B) Southern Chile (C) British Columbia and S.E. Alaska

danger Fjords of Norway), but more commonly they are fractured belts with closely spaced joints locally accompanied by faults and dykes. The pre-glacial rivers carved their valleys along these lines of least resistance. The valleys in turn confined the ice and guided its flow, and because the structure facilitated plucking, the valley floors were steadily deepened, often to an extraordinary degree. In some of the fjords of Norway and Patagonia the sea is over 4,000 feet deep. Neighbouring fjords, however, vary enormously in depth, in accordance with the varying resistance of the excavated rocks. The distribution of fjords is thus conditioned by (*a*) appropriate tectonic structures in upland regions near the sea, (*b*) pre-existing valleys which followed these structures, and (*c*) heavy glaciation by seaward-moving ice of sufficient thickness and surface slope to ensure that the main valleys were overdeepened up to or beyond the coast.

Glacial Deposits

As glaciers and ice sheets reach the zone of wastage beyond the region of active erosion they become overloaded and begin to drop their burden of debris. During the subsequent disappearance of the ice, in response to an amelioration of climate, the zone of deposition retreats with the receding ice front until the whole of the load has been deposited. The *glacial* deposits thus left stranded on the landscape and the *glaciofluvial* sands and gravels transported and deposited by the associated melt-waters have long been grouped together under the general term *drift*. At one time the vast spreads of drift that indicate the former extent of the ice across Europe and North America were thought to be flood deposits, and many attempts were made to assign them to the deluge of Noah. Eventually, however, it was recognized that the commonest type of drift, the haphazard assemblage of material known as *boulder clay* or *till*, could not possibly have been deposited by water.

Boulder clay has obviously been dumped down anyhow in a completely unsorted and unstratified condition (Plate 55A).

Its constituents range from the finest rock flour to stones of all sizes up to boulders that are occasionally of immense bulk. It usually consists of a varied assortment of stones embedded in a tenacious matrix of sand, clay, and rock flour. Most of the stones, like those of screes, are irregular fragments showing little or no sign of wear or tear, but a few can generally be found which have been rubbed down and scratched and grooved, clearly by scraping along the rocky floor over which they were dragged by the ice.

A characteristic feature of glaciated regions is the occurrence of scattered boulders of rocks that are foreign to the place where they have been dropped. These ice-transported blocks, carried far from their parent outcrops, are called *erratics*. The largest ones commonly rest on abraded surfaces where the normal drift is thinly scattered or confined to hollows. Some have been stranded in exposed and precarious positions. Such *perched blocks* (Plate 55B) are striking monuments to the former passage of ice, and as such they were amongst the first evidences of glaciation to be recognized. In 1815 Playfair pointed out that " a glacier . . . which conveys the rocks on its surface . . . is the only agent we now see capable of transporting them to such a distance." The long trails of erratic blocks of easily recognized rocks afford an unfailing guide to the direction of movement of the ice that carried them. Boulders of the well known Shap granite, for example, can be traced from their original home in Westmorland across the Pennines by way of the Stainmore Pass into the Vale of York. Ailsa Craig in the Firth of Clyde is an upstanding mass of finely speckled granitic rock which can be identified with certainty. Erratics of this rock, as isolated blocks and as stones embedded in boulder clay, are found in Antrim, Galloway, and the Isle of Man, and on both sides of the Irish Sea as far as Wicklow and South Wales, and show that Ailsa Craig lay in the track of a great southward-travelling glacier. Familiar Norwegian rocks from the Oslo district, such as rhomb-porphyry and larvikite (a shimmering blue syenite much used for shop fronts) occur as erratics along the Durham and Yorkshire coasts, and prove that the Scandinavian ice sheet crossed the North Sea and at

times overran the British shores. At other times these rocks reached northern Germany, showing that the directions of ice dispersal were not always the same.

At or near the maximum extension of a glacier or ice sheet the front may have remained stationary or nearly so (forward movement being just balanced by wastage) sufficiently long for a ridge-like *terminal moraine* to be heaped up. Similar, but later, terminal moraines, sometimes distinguished as *recessional*

[*Planet News Ltd.*

FIG. 118

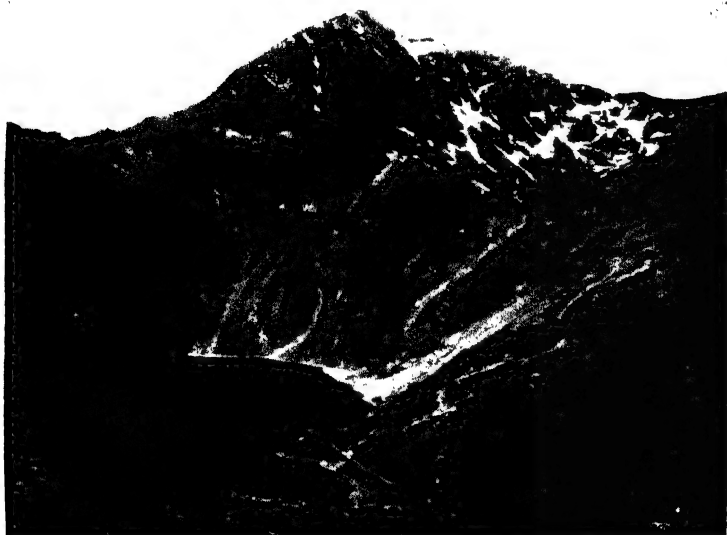
Lake on the Dontouz-Orun Pass, Caucasus Mountains, occupying an ice-eroded rock basin with a terminal moraine on the threshold

moraines, mark the sites of halting stages during the shrinkage of the ice, and indicate that forward flow was maintained so that a steady supply of debris was brought up to the ice front. In certain lowland regions the ice appears to have fanned out and become stagnant. Such " dead " ice simply melts away from the top and sides, and also from the edges of crevasses, and liberates its debris without forming terminal moraines.

The terminal and chief recessional moraines formed at successive stands of the European ice sheet are shown in Fig.

[*H.M. Geol. Survey*

(A) Loch Coruisk, Skye. A double rock basin excavated by ice. Cuillin Hills behind

[*G. P. Abraham, Ltd., Keswick*

(B) Snowdon and Glaslyn, viewed from Crib Goch, North Wales

[S. H. Reynolds

(A) Boulder clay on glaciated rock surface (bottom right-hand corner), Borrowdale, Lake District

[H.M. Geol. Survey

(B) Glacial erratic of Silurian grit resting on a plinth of Carboniferous Limestone, Norber, near Austwick, Yorkshire

127. Similar features, traversing the country in broad loops to the south of the Great Lakes, mark the various pauses in the recession of the North American ice. The terminal moraines left by mountain glaciers cross their valleys as crescent-shaped ridges (concave upstream) which in some cases continue along the valley sides as less conspicuous lateral moraines (Fig. 118). Many of the lakes of glaciated valleys are held up by morainic dams, and there were formerly innumerable smaller ones that

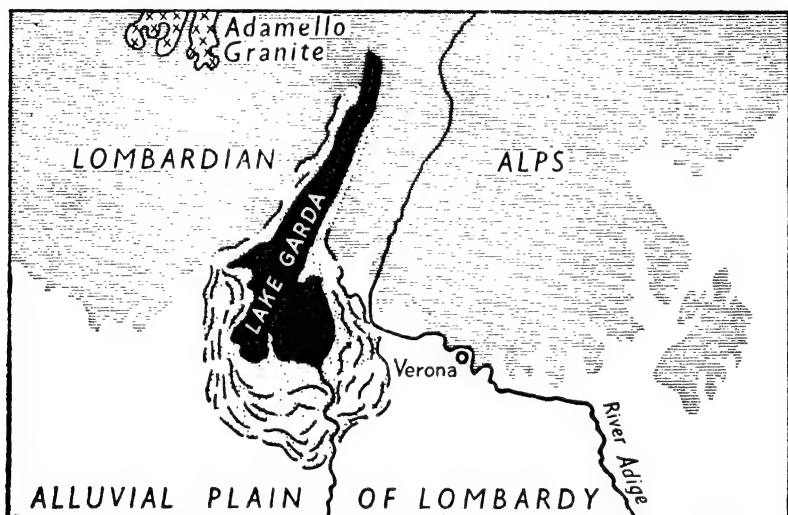



Fig. 119
Map of the lateral and terminal moraines bordering the rock basin of Lake Garda at the foot of the Italian Alps

have since been silted up or drained by a river gorge cut through the barrier. Lake Constance and Lake Garda (Fig. 119) are notable examples of lakes owing their existence to terminal moraines across the outer valleys of the Alps. Most of the larger lakes of the Lake District and many of the Scottish lochs have morainic dams.

In the tracts between the moraines the spreads of boulder clay naturally vary widely in character and thickness from place to place. In certain regions where the boulder clay is thickly plastered over a floor of low relief it has been moulded

by the ice into swarms of whale-backed mounds called *drumlins*. Being distributed more or less *en échelon* the mounds give rise to what has been aptly described as " basket of eggs " topography (Fig. 120). In the intervening depressions drainage is poor and confused, and is responsible for such features as ponds, marshes, and water-logged meadows. One of the most densely packed drumlin belts stretches across northern Ireland from Co. Down to Donegal Bay, and contains tens of thousands of these stream-lined mounds (Fig. 121).

Drumlins are commonly a quarter to half a mile long, but there is every gradation from low swells to enormous examples a mile or two in length and 100 to 200 feet high. Most of them are elongated in the direction of ice movement, and the end

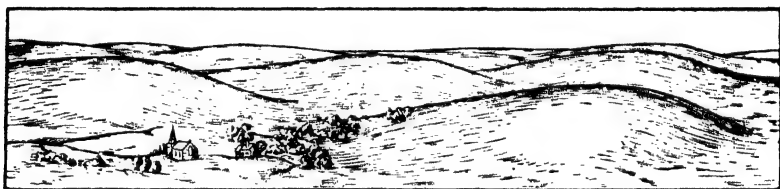



Fig. 120

" Basket of eggs " topography. A typical drumlin landscape moulded by ice which moved from right to left

facing upstream is characteristically blunt and steep compared with the tapering downstream end. The profile along the length is thus the reverse of that of a *roche moutonnée*. The latter being a product of ice erosion, it is reasonable to suppose that drumlins would have had a similar form if they had been moulded by over-riding ice from boulder clay already deposited. Since they have not this form, it becomes probable that drumlins were fashioned from ground moraine that was being freshly deposited by ice in which the capacity to erode, transport, and deposit was distributed in a curiously rhythmic pattern.

It is generally accepted that drumlins were formed under deep ice at a distance of several miles from the front towards which it was advancing. There must have been variations in the ice flow, possibly owing to such causes as (*a*) underlying

Fig. 121

Map showing part of a drumlin tract in Co. Down
(*After J. K. Charlesworth*)

obstructions—some drumlins have cores of solid rock with boulder clay banked against them ; (*b*) longitudinal crevasses in the ice which localized places of deposition ; and (*c*) variations in the load carried, the clearer and more vigorous ice flowing round the more heavily charged and sluggish ice. From the nature of the case, however, drumlins have never been seen in course of formation, and the exact mechanisms involved are still far from being clearly understood.

Glaciofluvial Deposits

The drainage from the long front of an ice sheet escapes by way of an immense number of more or less temporary and constantly shifting streams. These carry off a great deal of sediment and, as the velocity is checked, low alluvial fans or

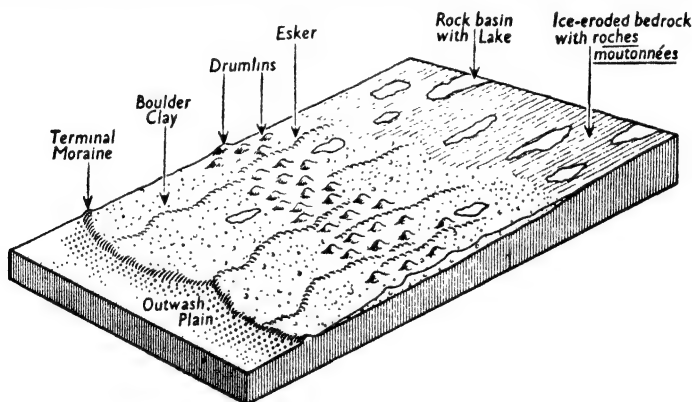



Fig. 122

The characteristic assemblage of features seen on a recently glaciated area of low relief

deltas are deposited, according as the ice terminates on land or in standing water. On land the fans spread out and coalesce into gently sloping *outwash plains* (Fig. 122) of irregularly stratified drift, ranging from coarse gravels near the source to sand further out, and finally to clay. Valley floors are choked with spreads of similar deposits ; mainly coarse, how-

[*H.M. Geol. Survey*

FIG. 123

Kettle hole near Finstown, Orkney

ever, because the finer materials are rapidly washed downstream.

Beyond the terminal moraines of ice sheets, where the supply of debris is abundant, outwash plains may extend for many miles. Vast areas of the North American prairies have been smoothly veneered with sediment in this way. Between successive moraines the outwash drifts rest on previously deposited boulder clay. Masses of stagnant ice, left stranded between deep crevasses as the main front melted back, are often surrounded and even buried by drift, and as they melt away they leave the surface pitted with depressions known as *kettle holes*. These are extremely irregular in shape and distribution, and many of them still contain lakes or ponds (Fig. 123).

Such drift-covered regions are further diversified by mounds (*kames*), long winding ridges (*eskers*, Fig. 124), and relatively short and straight ridges (*crevasse infillings*). All of these are built of crudely bedded gravel and sand, showing that they are features for which glacial streams were responsible.

FIG. 124
Esker, Tolvajärvi, Finland. The lake occupies the depressions in an irregular surface of glaciofluvial sands and gravels

Kames are isolated or clustered mounds, each of which represents a steep-faced localized alluvial cone or delta built up by a stream emerging at a high level from an ice wall, or perhaps between two confining walls at the head of an embayment in the ice front. As the ice withdrew, the unsupported back or sides of the accumulation slumped down, leaving a mound with slopes corresponding to the angle of repose of gravel or sand. If such a stream, instead of being short and temporary, were long and persistent, then the deposit continuously formed at its mouth would grow backwards as the ice retreated, thus extending into a winding ridge that would reproduce the course of the stream. Some *eskers* may have originated in this way. But such a stream would also deposit sediment while flowing through its tunnel in the ice, thus gradually raising its floor. Most eskers are therefore regarded as the infillings of the tunnels of unusually long sub-glacial streams. In some cases, where later outwash drift has lapped against them, it is obvious that they originated within the ice

before it receded. Eskers characteristically disregard the underlying topography, which they cross like long railway embankments, this form being assumed as a result of the inevitable slumping of the original sides. Their courses, though winding, are generally aligned more or less at right angles to the receding ice front. In glaciated lands riddled with lakes and marshes, like Finland and Sweden, eskers provide natural causeways across many districts where road and railway construction would otherwise be difficult. Ridges that differ from eskers in being short and straight are interpreted as the infillings of wide crevasses. They probably formed within large sheets of stagnant ice which melted away from the edges of the crevasses as well as from their sides.

Ice-dammed Marginal Lakes

A glacier occupying a main valley may obstruct the mouth of a tributary valley and so impound the drainage and form a lake. The Marjelen See, held up in this way by the Aletsch Glacier (between the Jungfrau and the Upper Rhone) is a small-scale example, and there are many others, large and small, in Norway, Iceland (Plate 56A), and Greenland. Where the ice barrier is sufficiently high and massive the lake rises to the col or pass at the head of its valley and escapes through an *overflow channel* into the valley on the other side. During the degeneration of an ice sheet into valley glaciers, the higher ridges of a divide between two neighbouring valleys may be uncovered, while the ice still extends across the divide at a lower level. Melt-water then accumulates along the margin of the ice against the flanks of the hills, and if it overflows from one side of the ridge to the other, a channel is cut in the ridge itself, which thus becomes notched. Notching by marginal overflow channels may be repeated again and again at successively lower levels while the ice is retreating.

During the recession of the great Pleistocene ice sheets enormous numbers of ice-dammed lakes came into existence

(*cf.* Fig. 126), some of them being immensely larger than any of the lakes of the present day. They formed wherever a drainage basin sloped down towards an obstructing ice dam. Some of these marginal lakes overflowed at successively lower levels before they eventually disappeared, each stand of the lake being determined by the height of the lowest outlet available at any given stage during the wasting away of the barrier. The features and deposits left behind by such lakes (thereby providing evidence of their former existence) include : (*a*) overflow channels at the outlets, often eroded into con-

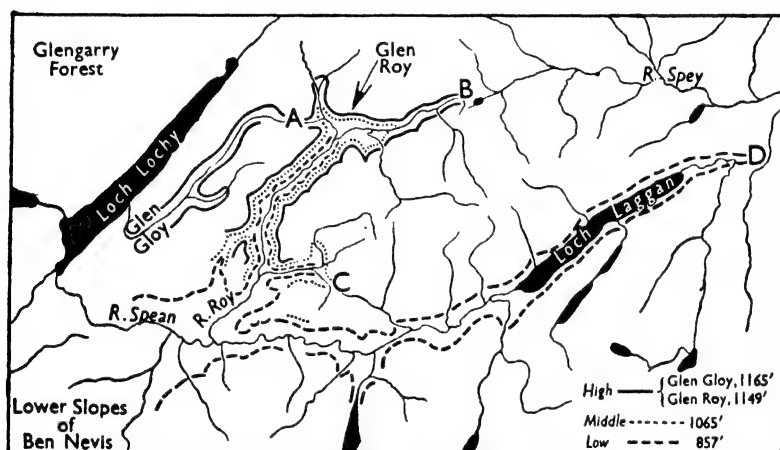



FIG. 125
Map of the Parallel Roads of Glen Roy

spicuous valleys and gorges (now dry) situated at the heads of the valleys from which the lake waters escaped, or across the ridges and spurs between neighbouring valleys ; (*b*) shore-line deposits and terraces, formed by the action of waves and currents ; (*c*) deltas deposited by streams flowing into the lake ; and (*d*) lake-floor sediments, including the *varved* sediments to be described later.

The most celebrated shore terraces of this kind are the Parallel Roads of Glen Roy (Plate 56B). These are beaches about 40 to 50 feet wide which follow the contours at the levels shown on the map (Fig. 125). Ice extending from Ben

Nevis across the valleys to the north blocked the entrances to Glen Roy and Glen Gloy. The highest lake (1,165 feet), that of Glen Gloy, discharged across the watershed at A into the Glen Roy lake (1,149 feet) which overflowed into the river Spey at B. Later, an outlet into a tributary of Glen Spean was uncovered at C (1,065 feet), and the lake rapidly drained to the level so determined. This stage, during which the waters escaped over the eastward-sloping surface of the Glen Spean ice, lasted until further withdrawal of the ice allowed the lake to extend along Glen Spean, whence it overflowed through D (857 feet), the outlet at its head. In due course the lobe of ice that blocked the lower part of the valley

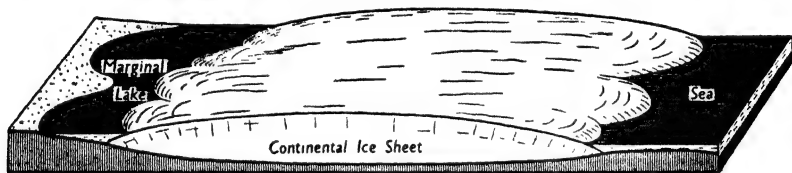



Fig. 126

Diagram to show the isostatic depression of a land surface loaded by a continental ice sheet, and the consequent development of marginal lakes during the recession of the ice. Vertical scale and slopes greatly exaggerated

dwindled away sufficiently to allow the lake to drain towards the sea (Loch Linnhe) and so, finally, to disappear.

During the recession of the continental ice sheets of Europe and North America conditions were highly favourable to the development of widespread marginal lakes (Fig. 126). At the time of maximum extension of the ice the less mountainous parts of the underlying floor were depressed into a shallow bowl by the isostatic effect of the load of ice. The thickness of the ice was of the order 6,000 feet, tapering off towards the margins. The corresponding subsidence of the crust, where the load was greatest, would therefore be about 1,600 feet; sufficient, that is, to depress vast areas of the rock surface well below sea level. During the retreat of the ice the crust was gradually unloaded and isostatic recovery worked in from the margins, though with a considerable lag. Consequently, for thousands of years there were large tracts, abandoned by the

ice, that sloped towards and beneath the receding ice front. Many of these became giant lakes, while others were invaded by the sea. The isostatic recovery already achieved since the disappearance of the ice is clearly demonstrated by the occurrence of raised beaches at various heights and by the tilted attitude of many lake terraces. Moreover, the fact that the shores of Hudson Bay and the Gulf of Bothnia are steadily rising even now shows that the process of restoring isostatic equilibrium is still going on. Actual depressions within the areas that were formerly inundated are, of course, still occupied by lakes or by the sea. The Great Lakes of North America and the Baltic Sea are outstanding examples.

From the sediments that accumulated on the floors of the marginal lakes in Europe the history of the ice recession can be deciphered with great accuracy almost all the way from the terminal moraines of Germany to the Scandinavian glaciers of to-day (Fig. 127). Each spring and summer, as the ice thawed, the lake in front received a supply of sand, silt, and clay from the streams that flowed into it. The coarser material settled down at once, but the finer particles remained in suspension much longer and were not completely deposited until much later in the year. But during the late autumn and winter the glacial streams were frozen and the lake, itself frozen over, received no further sediment. The still suspended mud slowly sank to the bottom, forming a thin layer of dark clay, easily distinguishable from the thicker layer of sandy silt beneath it. The following year the sediment liberated from the ice was again sorted out and deposited in two well marked seasonal layers, sharply separated from the underlying pair. Each such pair is called a *varve*, and the sediments characterized by this annual banding are described as *varved clays* (Plate 57B). As this process continued year after year the area of deposit moved northwards with the receding ice, and the varves thus became superimposed after the fashion of wedge-shaped tiles on a roof.

In 1885 Baron De Geer began to count the varves, starting in Scania at the southern end of Sweden. The thickness of the deposit at any one locality rarely exceeds 30 feet, but this

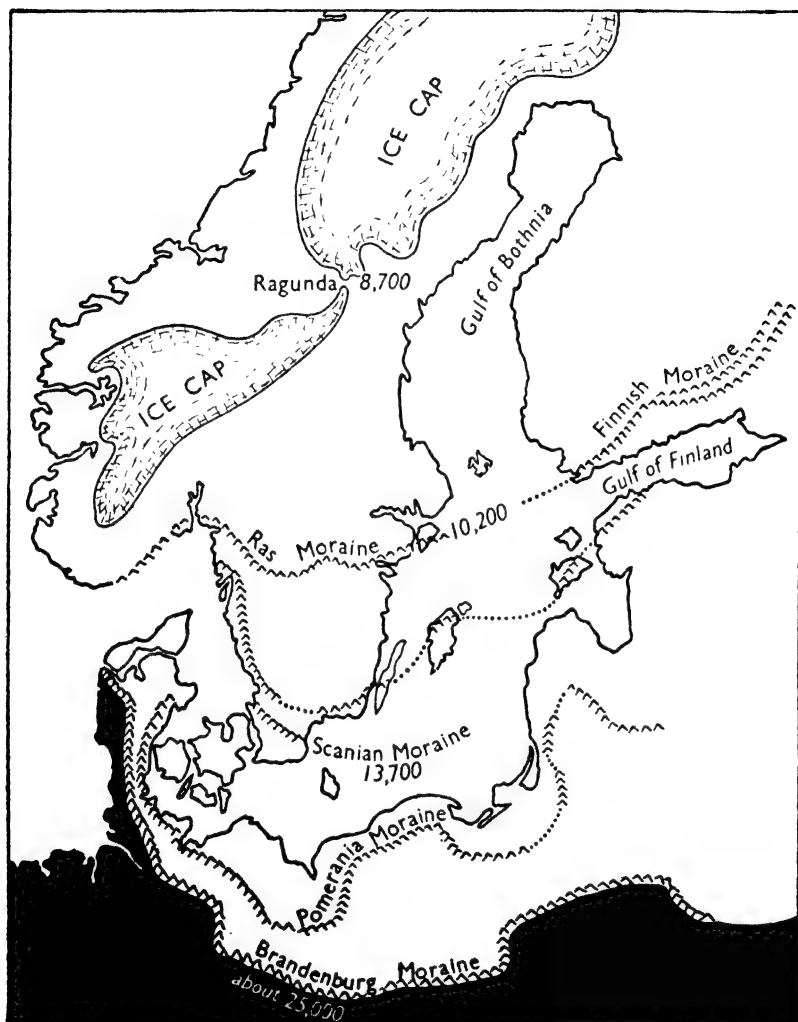



Fig. 127

Map to illustrate successive stages in the recession of the last European ice sheet, with dates (in years before 1900 A.D.) established by counting varves

may contain several hundreds of varves, each representing a single year. Those near the top can then be matched against the lower varves at a neighbouring locality to the north,

where the sequence includes the varves of the immediately succeeding years. Thus, by tracing the overlapping varves through sections and borings at more than 1,500 localities, and so carrying on the counting bit by bit, De Geer and his students succeeded, after thirty years of laborious work, in establishing an absolute chronology of the retreat stages of the last of the European ice sheets. The Ice Age is conventionally regarded as having ended about 8,700 years ago, when the ice sheet reached Ragunda and separated into two isolated caps (Fig. 127). Thirteen thousand seven hundred years have elapsed since the ice stood along the site of the Scanian moraine. From the Brandenburg moraine (marking the culmination of the ice) to the Scanian moraine the count is necessarily incomplete, because the sea now interrupts the sequence, but the gaps are few and the time of recession can be estimated without much error at rather more than 11,000 years. It is therefore approximately 25,000 years since the last European ice sheet began to disappear. The corresponding estimate in North America for the time elapsed since the Labrador ice sheet began its withdrawal from the Long Island terminal moraine is about 30,000 years.

Lakes : A General Summary

It will already have been gathered that lakes are amongst the most characteristic features of the landscape of glaciated regions. Finland is renowned for its innumerable lakes, 35,000 of which have been mapped. Very appropriately, the Finns call their country *Suomi*—the Land of Lakes. Many parts of Ontario and the neighbouring Provinces and States are riddled with a comparable network of lakes and waterways. The extraordinary abundance at the present time of lakes of glacial origin—they are far more numerous than all other types put together—is a result of two circumstances : (*a*) immense numbers came into existence on the irregular surface left behind by the retreating ice ; and (*b*) they originated so recently that only some of the shallower ones have since been eliminated.

Given a supply of water in excess of the amounts lost by evaporation or by seepage through the floor and sides, a lake continues to exist so long as the floor of its basin remains below the lowest part of the rim. Lakes are therefore conveniently classified according to the modes of origin of their basins. Those of glacial origin may occupy :

(*a*) ice-eroded rock basins in valleys or corries with or without morainic fringes (pages 219 and 224)
(*b*) valleys obstructed by morainic barriers (pages 228–29)
(*c*) depressions due to irregular deposition of glacial drift (page 230)
(*d*) kettle holes left by the melting of buried or partly buried masses of stagnant ice (page 233)
(*e*) valleys obstructed by ice barriers (page 235)

Among lakes with a more varied history, involving both glacial erosion and deposition, with modifications in many cases due to earth movements, the Great Lakes of North America are the most remarkable. Lake Superior, the largest freshwater lake in the world, is 1180 feet deep, and the bottom descends to 580 feet below sea level. The others have depths ranging from 210 to 870 feet. These immense basins were primarily gouged out by ice along the sites of broad pre-glacial valleys. Morainic barriers arranged in loops around their southern margins further increased their capacity. Isostatic changes of level, possibly combined with additional crustal warping due to independent earth movements, brought about other changes in their outlines and outlets. As the ice receded, marginal lakes accumulated in the depressions between the ice wall on the north and the moraines on the south. In successive stages, illustrated by Figs. 128 to 131, the overflow was, first into the Mississippi, then into the Hudson, and finally into the St. Lawrence. The upper lakes are somewhat delicately balanced just where lakes might have been least expected—on the watershed between the rivers flowing south to the Gulf of Mexico and north to Hudson Bay. A gentle tilt of their basins would suffice to send their waters southward

FIGS. 128–131.—Successive stages in the development of the Great Lakes of North America

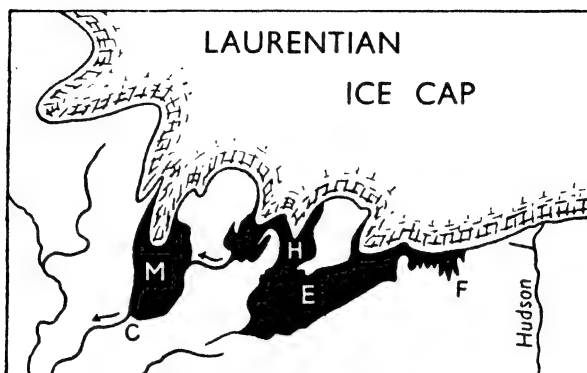



FIG. 128

An early stage (about 25,000 years ago), showing marginal lakes with an outlet near Chicago (C) into the Mississippi. For other lettering see Fig. 131

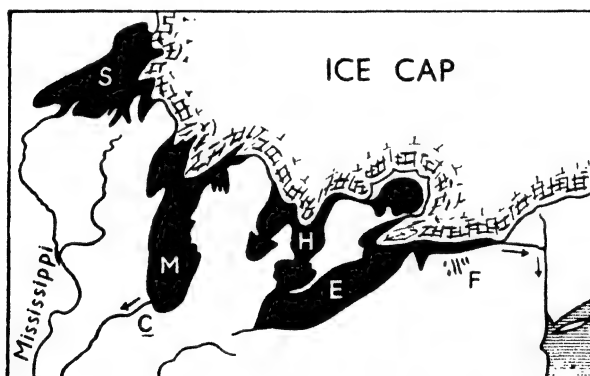



FIG. 129

The marginal ancestors of Lakes Superior and Michigan drain into the Mississippi. The eastern lakes drain into the Hudson River

instead of eastward. Isostatic up-tilting towards the north is still in progress, and the rate of movement is such that in about 1,500 years Lake Michigan will again drain to the Mississippi, unless some counterbalancing process (such as human interference) intervenes.

To the north-west another series of lakes originated in

Fig. 130
The upper lakes, swollen into the ancestral Lake Algonquin, drain, together with Lake Erie, into a seaway that occupied the St. Lawrence valley and extended over the site of Lake Ontario. An occasional overflow from Lake Michigan spills into the Mississippi

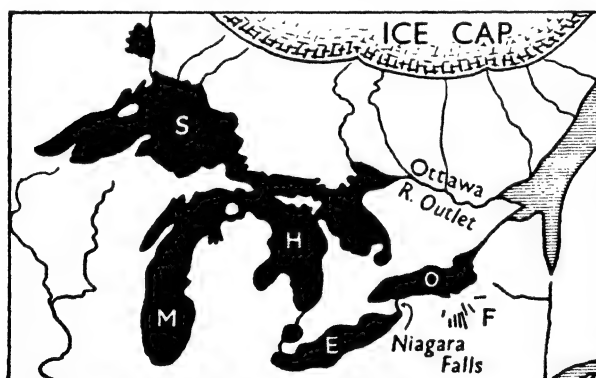



Fig. 131
The lakes approach their present-day outlines, the upper lakes draining into the dwindling St. Lawrence seaway through the valley of what is now the Ottowa River. E, Lake Erie ; F, Finger Lakes of New York State ; H, Lake Huron ; M, Lake Michigan ; S, Lake Superior

much the same way, beginning their history as marginal lakes which coalesced into a gigantic sheet of water referred to as Lake Agassiz. The flat-lying sediments of the floor of this vanished lake form the rich wheatlands of North Dakota and Manitoba. At first Lake Agassiz drained into the Mississippi,

but lower outlets were uncovered to the north later on, and the vast lake was reduced to remnants, including Lake Winnipeg, Lake Manitoba, and the Lake of the Woods. In Europe Lakes Ladoga and Onega had a similar origin and history.

Lake basins owing their origin to other geological processes are described in the appropriate chapters, but for convenience the following summary is added here.

Lake Basins due to Earth Movements

Tectonic depressions are responsible for the largest of the world's lakes (Caspian Sea), the deepest (L. Tanganiyka), the lowest (Dead Sea), and amongst those of notable size the highest (L. Titicaca, Bolivian plateau), as well as for many shallow lakes, both large (L. Victoria) and small (local sinkings of the ground accompanying earthquakes). In terms of origin the chief types are due to :

Crustal Warping (L. Victoria, page 431 ; Lough Neagh) and the backtilting of valley systems (L. Kyoga, page 432).

Differential Faulting, especially in the African Rift Valleys (page 432) and in the Great Basin of the Western States (page 423).

Tear Faults across a pre-existing valley, whereby it may be obstructed by a hill range (L. Joux, Jura Mountains; Fahlensee, Santis Alps).

Lake Basins due to Volcanic Activity

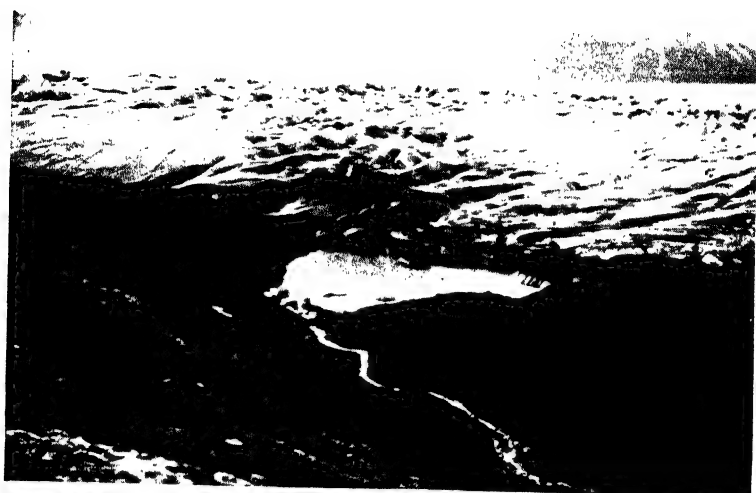
Craters and *Calderas* of extinct or dormant volcanoes (Crater Lake, Oregon, Plate 94).

Lava Flows forming barriers across valleys (Sea of Galilee ; L. Kivu).

Lake Basins due to Deposition of Sediments

Obstruction of valleys and river channels may be brought about by :

Landslides (page 148) and occasionally by avalanches and screes.

River Deposits : Delta growth from relatively vigorous side streams. The sealing off at both ends of abandoned meander

[L. Hawkes

(A) Ice-dammed lake on side of the Hoffell Glacier, Hornafjord, south-east Iceland

 [H.M. Geol. Survey

(B) The Parallel Roads of Glen Roy, Inverness-shire

[H.M. Geol. Survey

(A) Moraines and moraine-dammed lochans. Valley of Allt a'Choire Mhor, Ross-shire

[R. W. Sayles

(B) Varved sediments, Vermont. The upward thinning of the varves is an indication of ice recession

loops (ox-bow lakes, page 165). Levee building in general (flood plain lakes and swamps and delta lagoons, page 168 and Fig. 79). Norfolk Broads (pages 194–95).

Glacial Deposits (see above).

Wind Deposits : Coastal sand dunes enclosing lagoons and marshes (as in the Landes of south-west France).

Marine Deposits : Closed bars and barrier beaches enclosing coastal lagoons (page 299).

Lake Basins due to Denudation

It should not be overlooked that the depressions occupied by an immense number of barrier lakes are river valleys that have been locally obstructed. The following processes are directly responsible for the excavation of basins :

Solvent Action of Ground-water: Swallow holes, of which the outlets have been clogged by residual clays. Surface subsidences due to underground solution of limestone (page 134) or of rock salt (the meres of Cheshire).

Solvent Action of Rivers : Expansion and deepenings of river beds by surface solution of limestone (some of the Alpine lakes; Lough Derg, an expansion of the River Shannon).

Glacial Erosion (see above).

Wind Deflation : Hollows excavated in arid regions to a depth where an adequate supply of ground-water is tapped.

The Pleistocene Ice Age

The maximum extent of the Pleistocene ice sheets in the Northern Hemisphere is shown in Fig. 132. The total area overwhelmed by ice approached eight million square miles. Half of this was in North America, where the ice radiated from three main centres : Labrador, the Keewatin district bordering Hudson Bay, and the Cordilleran ranges of the west. The European ice and its continuation beyond the Urals covered nearly three million square miles. A subsidiary ice cap radiated from the Alps, and the Himalayas and other ranges of Asia were similarly glaciated. It is remarkable that some of the

FIG. 132
Map showing the maximum extent of the Pleistocene ice in the Northern Hemisphere. (*After E. Antevs*)

Arctic islands and also much of Siberia (*cf.* page 204) appear to have escaped general glaciation. In recent years, however, Soviet geologists have been finding increasing evidence that the ice spread over wider areas than those shown on Fig. 132.

In the Southern Hemisphere the Kosciusko plateau of New South Wales and a considerable part of Tasmania were glaciated. New Zealand, where glaciers still persist, was largely shrouded in ice, and so were extensive tracts of Patagonia and southern Chile. The Antarctic sheet, like that of Greenland, was thicker and more extensive than it is to-day. In Central Africa moraines occur more than 5,000 feet below the ice that still remains on Ruwenzori and the higher volcanic peaks (see Plate 45). The climatic changes evidently led to a general lowering of the snow line, and were clearly world-wide in their effects.

Detailed studies of the drift deposits have shown that

glaciation was not confined to the effects of a single great advance and retreat of the ice. In many places around the Alps four successive sets of boulder clays, moraines, and outwash gravels are preserved, showing that there was a fourfold repetition of the glacial cycle. The fourth and latest cycle, of which naturally most is known, appears to have involved one or two minor advances and retreats before the final withdrawal to present conditions. The intervals between the major glacial phases—known as *interglacial stages*—are represented by ancient soils, and locally by lake and river deposits or screes, sandwiched between older and younger beds of glacial or glaciofluvial drift.

Some of the interglacial beds contain plant remains, and so provide valuable information as to the climatic conditions at the times when they were deposited. A consolidated scree, formed during the third interglacial stage, and still preserved as a thick wedge of breccia near Innsbruck, contains fossil leaves and other relics of trees that no longer grow in the Alps but only in warmer regions. At that time the average temperatures in the Alpine region must have been higher than now, and quite possibly it was then too warm for glaciers to be nourished at all. From similar lines of evidence elsewhere it appears that the first interglacial stage was also relatively warm, but that the second was cooler, with a climate comparable to that of the present.

The four major Alpine glaciations and the intervening interglacial stages are known by the names listed in the following table, the names being those of places where the glacial deposits so distinguished are well exposed. Attempts have been made to estimate the durations of the interglacial stages by comparing the effects of weathering and erosion on the underlying deposits in each case. The depth reached by weathering during Riss-Würm time is found to be about three times that achieved on similar but later deposits exposed during post-Würm time. Since the latter is about 25,000 years, it follows that the Riss-Würm interval cannot have been less than 75,000 years. Indeed, it may well have been considerably longer, because the second foot of weathering—other

Major climatic cycles	GLACIAL and *Interglacial* Stages (Alps)	Relative durations estimated from depth of weathering	Corresponding periods in years	Comparable estimates from Iowa, U.S.A.
4	*Post-Würm*	1 representing	25,000	25,000
	WÜRM		?	? 30,000
3	*Riss-Würm*	3	75,000	120,000
	RISS		?	?
2	*Mindel-Riss*	12	300,000	300,000
	MINDEL		?	?
1	*Günz-Mindel*	3	75,000	200,000
	GÜNZ		?	?

things being equal—takes considerably longer than the first, and so on. The figures in the table are therefore to be regarded as minima. Estimates from America based on the same comparative method are given in the last column. Allowing for the very considerable margin of uncertainty, it can hardly be less than a million years since the first great ice sheet began its advance—and it may well be more.

What of the future? Reference to Fig. 133 shows that during the latest chapter of the earth's history there have already been four major climatic cycles. Clearly we can have no assurance that these remarkable oscillations have come to an end. The persistence of the Greenland and Antarctic ice sheets shows that, strictly speaking, the Ice Age is still with us. But even though the former severity has relaxed, it is important to realise that present conditions are themselves, geologically speaking, very unusual. Ice ages have been quite exceptional during the earth's history, and it is to be expected that sooner or later there will be a return to the milder and more normal climates that have characterised most of the geological past. Ice sheets will then be banished from the globe.

Meanwhile—apart from the remote possibility that present conditions will persist indefinitely—the future holds out the prospect of one of two alternatives. It may be that we are now living in the early years of a cool interglacial stage, comparable with that of the Mindel-Riss, to be followed by yet

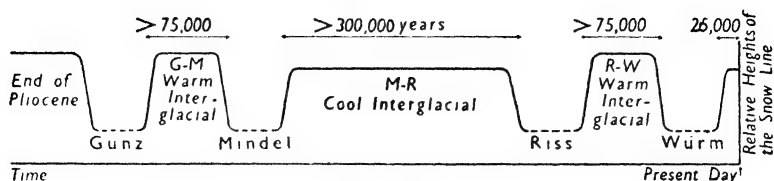



FIG. 133

Diagrammatic representation of the climate cycles in the Alps during the Pleistocene, showing the four major ice advances and the intervening interglacial stages

another glaciation which, this time, would relentlessly obliterate many of the most cherished homes of mankind. On the other hand, the present may be merely a pause during the slow restoration of a more genial climate under which the existing ice-sheets will melt away. If this happens, the liberated melt-waters will raise the level of the oceans by about 100 feet. London and New York and all other ports and lowland cities throughout the world will then be submerged, and obliged to migrate to higher sites. Either alternative is sufficiently alarming to justify the most careful study of present-day climatic tendencies, and of the possible causes of ice ages.

SUGGESTED CAUSES OF ICE AGES

If we knew how to explain the strange vicissitudes of climate that have occurred in the past, we might be able to forecast future developments more confidently. But so far this highly complex problem remains unsolved, although many plausible hypotheses have been proposed. Only a brief outline of the more important suggestions can be given here.

Changes in the Bodily Movements of the Earth, e.g. in the eccentricity of the earth's orbit, and in the inclination of the earth's axis to the ecliptic. These are real periodic changes, and since they must be accompanied by correspondingly periodic climatic variations, they must have a genuine bearing on the climatic problem. If, however, the variations reached ex-

tremes sufficient to account for the glaciations of the Pleistocene, there should have been hundreds of similar ice ages since the Cambrian period. Actually, there has been only one other comparable case during the last five hundred million years—at the close of the Carboniferous period (see page 499). It may therefore be concluded that, by themselves, these changes are inadequate.

Changes in the Position of the Poles relative to the Continents or vice versa.—It is generally agreed that movements of the poles on a scale sufficient to bring about important climatic changes are highly improbable. The earth behaves like a gyroscope and only very slight changes in the position of the axis are dynamically possible. It is much less improbable that the outer crust may have moved over the interior, or that the continents may have changed their positions relatively to one another. Continental drift (discussed in Chapter XXI) might account for the *distribution* of certain glaciated areas, particularly in the late Carboniferous, when India and Central Africa were amongst the glaciated lands ; but neither continental drift nor polar wandering begins to explain how these areas came to be glaciated at all. Polar ice caps are exceptional features in the earth's history, and a region does not automatically receive a shroud of ice merely because it happens to lie over or near one of the poles.

Changes in Topography.—Mountain growth and continental uplifts have occurred at intervals during geological time, and if such elevated regions rose above the snow line glaciation would obviously be favoured. Moreover, changes in topography, and in the distribution of land and sea, affect the circulations of moisture-laden winds and of oceanic currents, both of which affect in turn the height of the snow line and climatic conditions generally. Here, then, we have an important contributory factor, but certainly not a sufficient one in itself, for there is no correlation between the times of maximum elevation and those of widespread glaciation. Conversely, the late Carboniferous ice sheets developed over lands that were for the most part low-lying.

Changes in the Composition of the Atmosphere.—The carbon dioxide of the air absorbs a small amount of the heat reflected from the lands. It has therefore been suggested that increase in the proportion of atmospheric carbon dioxide would lead to a rise of temperature, and decrease to a fall of temperature. The effect is very slight, and is almost wholly offset by complementary effects due to water vapour. Appeal has also been made to the fact that after paroxysmal volcanic eruptions (*e.g.* Krakatao in 1883, page 470) the dust blown into the air reflects back some of the sun's rays, and so brings about a temporary drop of temperature. There is, however, no correlation between times of prolonged volcanic activity and times of glaciation.

Changes in the Sun's Radiation.—Small-scale variations in the the amount of heat received from the sun are known to occur, especially in connection with the sun-spot cycle. This fact has stimulated what is perhaps the most promising of all the ideas so far proposed : the hypothesis that there may be large-scale fluctuations in the sun's radiation, recurring at very long intervals. When we consider that the earth has orogenic cycles of 200 million years or so, reflecting the behaviour of its interior, it seems not unreasonable to suppose that the sun may also be subject to long-period disturbances arising from within it. The difficulty about this hypothesis is not that it is inadequate, but that it cannot be tested and therefore cannot be either proved or disproved. It may very well be true, but for the present it remains no more than an attractive speculation.

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Chapter XIII

WIND ACTION AND DESERT LANDSCAPES

The Geological Work of Wind

As an agent of transport, and therefore of erosion and deposition, the work of the wind is familiar wherever loose surface materials are unprotected by a covering of vegetation. The raising of clouds of dust from ploughed fields after a spell of dry weather and the drift of wind-swept sand along a dry beach are known to everyone. It is with this direct action on the land surface that we shall be concerned in this chapter. But it should not be overlooked that the wind also distributes moisture over the face of the earth, and is therefore one of the primary factors responsible for weather and weathering and for the maintenance of rivers and glaciers. Moreover, by transferring part of its energy to the surface water of the sea, the wind is responsible for waves and their erosive work.

In humid regions, except along the seashore, wind erosion is limited by the prevalent cover of grass and trees and by the binding action of moisture in the soil. But the trials of desert warfare have made it hardly necessary to stress the fact that in arid regions the effects of the wind are unrestrained. The " scorching sand-laden breath of the desert " wages its own war of nerves. Dust storms darken the sky, transform the air into a suffocating blast, and carry enormous quantities of material over great distances (Fig. 134). Vessels passing through the Red Sea often receive a baptism of fine sand from the desert winds ; and, beyond the other end of the Sahara, dunes have accumulated in the Canary Islands from sand blown across the intervening sea. Red dust sometimes falls in Italy, and even in Germany, carried north by great storms from the Sahara. The " blood rains " of Italy are due to this same red dust washed down by rain from the hazy atmosphere.

[E.N.A.

FIG. 134

Dust storm approaching Port Sudan

By itself the wind can remove only dry incoherent deposits. This process of lowering the land surface is called *deflation* (L. *deflare*, to blow away). Armed with the sand grains thus acquired, the wind near the ground becomes a powerful scouring or abrading agent. The resulting erosion is described as *wind abrasion*. By innumerable impacts the grains themselves are gradually worn down and rounded. This third aspect of wind erosion, the wear and tear of the " tools," is distinguished as *attrition*.

The winnowing action of the wind effectively sorts out the transported particles according to their sizes. This is well illustrated in the desert wherever mixed deposits of gravel, sand, and mud are worked over by the wind. Such materials are continually liberated by weathering and abrasion from bedrock surfaces, but far larger supplies are furnished by sheets of poorly assorted alluvium spread over the desert floor by the occasional torrents that flush out the wadis. Particles of silt and dust are whirled high into the air and transported

far from their source, to accumulate beyond the desert as deposits of loess (page 267). Sand grains are swept along near the surface, travelling by leaps and bounds, until the wind drops or some obstacle is encountered. The dunes and other accumulations of wind-blown sand thus come to be composed of clean and uniform grains, the finer particles having been sifted out and the larger fragments left behind. It follows that pebbles and gravel are steadily concentrated on the wind-swept surfaces of the original mantle of rock-waste.

As a result of wind erosion, transport, and deposition three distinctive types of desert surface are produced :

(1) The rocky desert (the *hammada* of the Sahara), with a surface of bedrock kept dusted by deflation and smoothed by abrasion (Plate 61A) ;

(2) the stony desert, with a surface of gravel (the *reg* of the Algerian Sahara), or of pebbles (the *serir* of Libya and Egypt) ; and

(3) the sandy desert (the *erg* of the Sahara).

Complementary to these is the loess of the bordering steppes, deposited from the dust-laden winds that blow from the desert.

Wind Erosion

The most serious effects of wind deflation—from the human point of view—are experienced in semi-arid regions like the Great Plains west of the Mississippi, where in recent years vast quantities of soil have been blown and washed away from thousands of formerly productive wheat-growing farms. Originally an unbroken cover of grass stabilised the ground, but long-continued ploughing and over-exploitation finally destroyed the binding power of the soil and exposed it as a loose powder to the driving force of the wind. This national menace became critical during a period of severe droughts, culminating in 1934–35, when great dust storms originating in the " Dust Bowl " of Kansas swept over the States towards the Atlantic.

Rainwash and the creeping disease of badland erosion extended the devastation. Widespread measures of reclamation and protection have been undertaken to minimise the growing wastage and desolation.

A characteristic result of deflation, especially over regions where unconsolidated clays and friable shales are exposed (*e.g.* in the North African, Kalahari, and Mongolian deserts), is the production of wide plains and basin-like depressions. The excavation of hollows is limited only by the fact that even in deserts underground water may be present. Once the desert floor has been lowered to the level of the ground-water, the wind can no longer pick up the moistened particles. The base level for wind action is that of the water table, which may be far below sea level. The "pans" of South Africa and the Kalahari and the more impressive depressions and oases of Egypt and Libya have all been excavated by ablation.

Westward from Cairo to Jarabub there is a remarkable series of basins with their floors well below sea level (Fig. 135), reaching -420 feet in the salt marshes of the immense Qattara depression. Some of the smaller basins tap a copious supply of ground-water at depths of -50 to -100 feet, and have become fertile oases. To the north the surface rises by abrupt escarpments to terraced tablelands formed of hard sandstones and limestones which formerly extended across the softer rocks of the depressions. To the south, following the direction of the prevailing wind, long stretches of sand dunes represent part of the removed materials. The other well-known oases of Egypt—Baharia, Farafra, Dakhla, and Kharga—are above sea level, but they have originated in the same way. All of them have steep escarpments of resistant rock to the north, and Baharia is entirely enclosed within rocky walls. The floors consist of the same soft strata as those found at the base of the escarpments. The depressions are not crustal sags, nor have they been cut by water, for the intermittent floods due to rare cloudbursts tend to fill them up with debris. The wind has been the sole excavator.

The effects of wind abrasion are unmistakably expressed
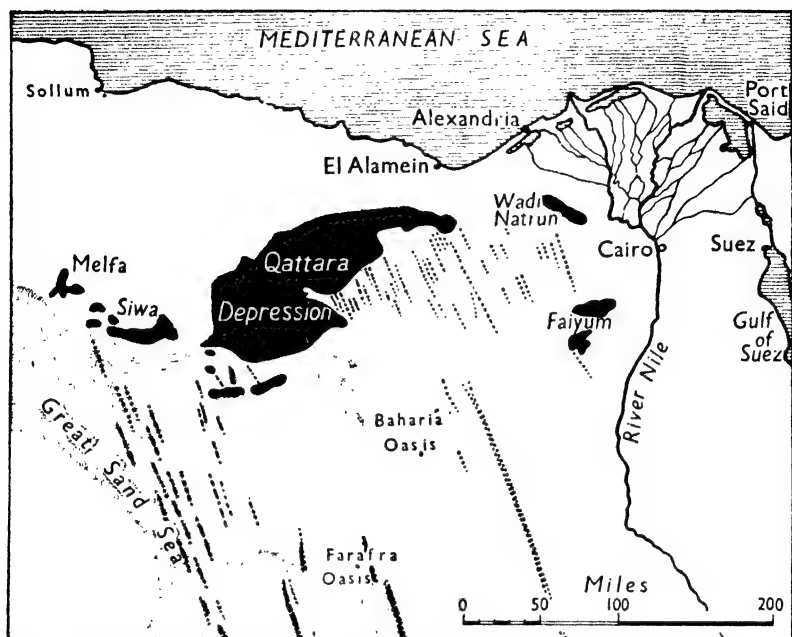
Fig. 135
Map showing depressions, sand wastes, and lines of sand dunes in the Egyptian Desert

in the forms and surfaces of the desert bedrocks. Just as an artificial sand blast is used to clean and polish building stones and to etch glass, so the natural sand blast of the wind attacks destructively everything that lies across its path. Cars driven against wind-blown sand may have their wind-screens frosted and their paint scoured off. The action on exposed rocks is highly selective. Like a delicate etching tool, the sand blast picks out every detail of the structure. Hard pebbles, nodules, and fossils are left protruding from their softer matrix until they fall out. Variably cemented rocks are fritted and honey-combed like fantastic carvings. Where there are thin alter-nations of hard and soft strata the soft bands are scoured away more rapidly than the hard, which thus come to stand out in strong relief, like fluted shelves and cornices with deep grooves between. Where the wind blows steadily in one direction

over strata of this kind, especially if the beds are tilted rather than flat, the softer materials are excavated into long passage-ways (parallel to the dominant wind direction) separating deeply undercut, overhanging ridges. Such fantastically carved " cockscomb " ridges are common in certain parts of the Asiatic deserts, where they are called *yardangs*.

Undercutting is everywhere a marked feature of wind abrasion, owing to the fact that the process is most effective just above the surface, where the sand is most abundant. Telegraph poles in sandy stretches of desert have to be protected by piles of stones against the cutting action of the sand grains hurled against them. Along the base of escarpments alcoves and small caverns may be hollowed out. As always, the effect of undercutting on slowly weathered formations is to maintain steep slopes. Joints are readily attacked and opened up and these commonly determine the outlines of rock towers and pinnacles, left isolated like detached bastions in front of the receding wall of an escarpment (Plate 64). Upstanding rocks attacked at the base by winds from varied directions pass through a stage in which they resemble mushrooms, especially when a resistant cap-rock overlies a weaker formation.

Where the bedrock of the desert floor is exposed to blown sand it may be smoothed or pitted or furrowed, according to its structure. Compact limestones become polished, massive granites are smoothed or pitted, and gneisses and schists are ribbed and fluted parallel to their foliation. Where pebbles have become sufficiently concentrated by removal of finer material they become closely packed, and in time their upper surfaces are ground flat. In this way mosaic-like tracts of *desert-pavement* are developed. Isolated pebbles or rock fragments strewn on the desert surface are bevelled on the wind-ward side until a smooth face is cut. If the direction of the wind changes seasonally, or if the pebble is undermined and turned over, two or more facets may be cut, each pair meeting in a sharp edge. Such wind-faceted pebbles, which often resemble Brazil nuts, except that their surfaces are polished, are known as *dreikanter* or *ventifacts* (Fig. 136).

FIG. 136
Pebbles faceted by sand blast (dreikanter or ventifacts). Drawn by M. V. Binosi from specimens in the Cairo Geological Museum. (*From W. H. Hume, "Geology of Egypt," Vol. I., by permission*)

As a result of continual attrition due to the friction of rolling and impact the sand grains themselves are gradually worn down and rounded. The prolonged action of wind is far more effective in rounding sand grains than that of running water, because of (*a*) the greater velocity of the wind ; (*b*) the greater distances traversed by the grains as they bound and roll and collide with each other backwards and forwards across wide stretches of desert ; and (*c*) the absence of a protective sheath of water. Some of the *millet seed sands* of the desert are almost perfect spheres with a mat surface like that of ground glass. It is also noteworthy that visible flakes of mica, such as are commonly seen in water-deposited sands and sandstones, are very rare in desert sands and dunes. The easy cleavage of mica facilitates constant fraying during the wear and tear of wind action. Mica is thus reduced to an impalpable powder that is winnowed away from the heavier sand grains. These

contrasts between water-laid and aeolian sands are of great value in deciding whether ancient sandstones have been formed in deserts or under water. The Penrith Sandstone of the Eden valley is a well-known example of a Permian desert sand. Its rounded grains, the absence of mica, and the cross-bedding of the formation all testify to the desert conditions of the time.

Coastal Dunes and Sandhills

Along low-lying stretches of sandy coasts and lake shores, where the prevailing winds are onshore, drifting sand is blown landwards and piled up into dunes which form a natural bulwark of sandhills. Any mound or ridge of sand with a crest or definite summit is called a *dune*. Deposition begins wherever the force of the wind is broken by obstructive irregularities of the surface, including grasses and trees. In humid regions the
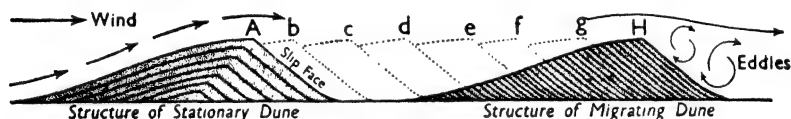
Fig. 137

Sections to illustrate the growth, migration, and structures of sand dunes. A stationary dune, A, grows in height with a forward and upward advance of the crest. When the sand supply and wind velocity involve migration of the dune, the crest advances to positions such as *b*, *c*, . . . *g*, and H

conditions governing growth and removal are very complex. The wind varies in strength and direction. Vegetation and moisture tend to fix the sand, but fixation is often incomplete. During severe gales old dunes may be breached and scooped out into deep " blow outs." The resulting confused assemblage of hummocks and hollows gives coastal sandhills a characteristically chaotic relief.

An ideal dune has a long windward slope rising to a crest and a much steeper leeward slope (Fig. 137). The latter is determined by the fact that sand blown over the crest falls into a wind shadow, and comes to rest at its natural angle of repose—about 30° to 35° for dry sand. The windward slope

[*H.M. Geol. Survey*

(A) A stage in the forward drift (from right to left) of the Culbin Sands, Moray

[*H.M. Geol. Survey*

(B) Maviston Sandhills (south-west continuation of the Culbin Sands), partially arrested by bent, Moray

[*H.M. Geol. Survey*

(A) Advancing sand overwhelming a plantation of Scotch firs

[*H.M. Geol. Survey*

(B) Remains of a plantation formerly buried by sand which has now drifted farther on

MAVISTON SANDHILLS, MORAY

is often beautifully rippled (Plates 5A and 60A). In situations where dunes are not effectively arrested by vegetation, or kept within bounds by winds from opposing quarters, they slowly migrate in the direction of the prevailing wind. When the wind is not fully loaded with newly acquired sand it sweeps up more from the windward slope, and drops it over the crest, where it streams down the "slip-face." By subtraction of sand from one side and addition to the other the dune travels forward.

As one belt of dunes is driven inland away from the beach, another arises in its place "so that a series of huge sandy billows, as it were, is continually on the move from the sea-margin towards the interior" (Plate 58A). Very wide belts of sandhills have spread inland in this way along the coasts of Holland and North Germany and in the Landes of Gascony adjoining the Bay of Biscay. The Culbin sandhills, near the mouth of the Findhorn on the southern shore of the Moray Firth, furnish a classic example of the destruction of cultivated lands and habitations by advancing sand. Prior to 1694 the sandhills had already reached the fringe of the Culbin estate. In that year a great storm started a phase of accelerated encroachment which finally led to the complete obliteration of houses, farms, and orchards, and even to the burial of fir plantations (Plate 59).

In many threatened regions measures have been taken to restrain the advance of the dunes. Tough binding grasses such as bent or marram are excellent for this purpose (Plate 58B). The harsh tufts check the wind, trap oncoming supplies of sand, and continue to grow outwards as the entangled sand accumulates, leaving behind them an intricate network of long roots. Such protected dunes become levelled up and turfed over. Subsequent growth of the dunes then tends to be seawards. Where the problem is less easily solved, as in the Landes, the dunes are anchored more securely by starting plantations of conifers on the landward side, and gradually extending them across the sand already partially fixed by grasses.

Desert Dunes and Sand Sheets

About a fifth of the land surface is desert, and on an average about a fifth of the desert areas is mantled with sand. A high proportion of the desert floor is an erosion surface of bedrock, locally strewn with coarse rock-waste (Plate 61A). Regions of shale and limestone provide little or no sand, but where sandstone is being disintegrated or mixed alluvium is being deflated, the wind picks up the loose grains and concentrates them into vast sand wastes (Plate 60) and long chains of dunes.

Complications due to vegetation and moisture arise only around oases or in the transition zones where the desert merges

Fig. 138
A typical barchan (drawn from a photograph)

into steppe or savanna country. In the heart of the desert the wind has free play. But nevertheless, as a masterly study by Brigadier Bagnold has made abundantly clear, the factors controlling the form of the sand accumulations are far from simple. They include the nature, extent, and rate of erosion of the source of supply ; the sizes of the sand grains and associated fragments ; the varying strength and direction of the wind ; and the roughness or smoothness of the surface (*e.g.* the presence or absence of pebbles) across which the sand is drifted and deposited. Of the resulting sand forms four main types can be distinguished :

(*a*) *Sand drifts* caused by protruding rocks or cliffs. These call for no further mention.

(*b*) *Crescentic dunes* or *barchans* (a Turkestan name which has been generally adopted), which occur as isolated units (Fig. 138), either sporadically or in long chain-like

swarms, or as colonies, more or less linked together laterally, which advance across the desert like gigantic but irregular ripples.

(*c*) *Linear ridges* or *longitudinal dunes* (known as *seifs* in the Sahara), which commonly occur in parallel ranges of immense length, each diversified by peak after peak " in regular succession like the teeth of a monstrous saw."

(*d*) *Sand sheets* of wide extent, which may be flat or undulating (Plate 60 and Fig. 141).

Dunes arise wherever a sand-laden wind piles up sand on the slopes of a random patch. The mound grows in height until a " slip-face " is established by avalanching on the sheltered leeward side. As the dune migrates, the extremities, offering less resistance to the wind than the summit region, advance more rapidly, until they extend into wings of such a length that their total obstructive power becomes equal to that of the middle of the dune. The resulting crescentic form then persists with only minor modifications of shape and size, so long as the wind blows from the same quarter. The width of a barchan is commonly about a dozen times the height, which ranges up to a maximum of 100 feet or so. Winds blowing continually from nearly the same direction are essential for the growth and stability of barchans. Under such conditions, and given a sufficient supply of sand, elongated swarms of barchans march slowly forward, like a stream of vehicles in a one-way street (Fig. 139). The rate of progress varies up to 20 feet a year for high dunes, and up to 50 feet a year for small ones.

Where the prevailing wind is occasionally interrupted by strong cross winds which drive in sand from the sides, the conditions are like those of a one-way street which becomes densely crowded and choked by the inflow of traffic from every cross-road. Instead of a chain of barchans, a long seif dune is developed, a high, continuous, but serrated ridge parallel to the direction of the prevailing wind, and in some examples running dead straight for a hundred miles or more. In South
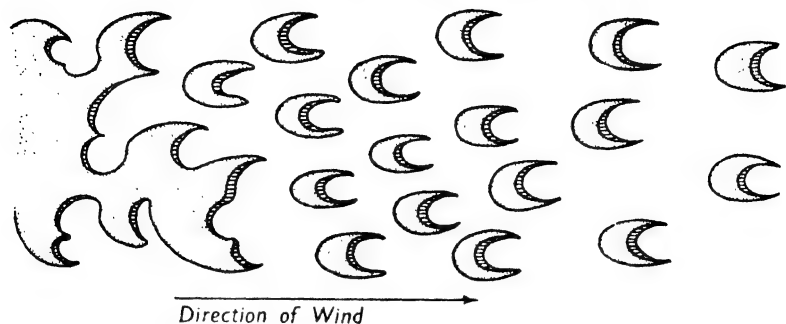
FIG. 139
Plan of a procession of barchans in the Libyan Desert

Iran such ridges occasionally reach a height of 700 feet. In Egypt 300 feet is common. S.S.E. of the Qattara depression there is a long tract of many parallel seifs with corridors of bare desert floor between (Fig. 135). One of the most remarkable features of desert dunes is their apparent power of
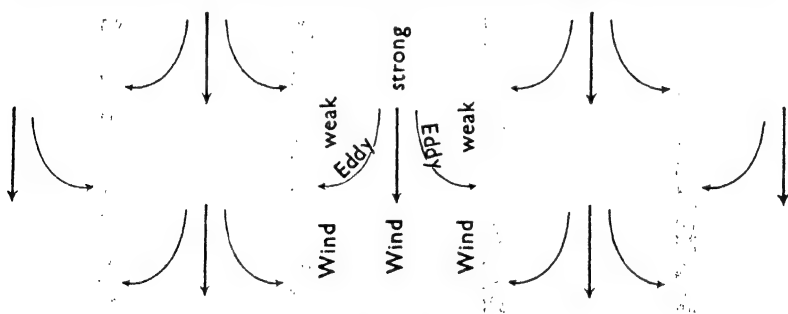
FIG. 140
Diagram to illustrate the shepherding effect of wind on sand ridges. The wind is strongest between the ridges, and is retarded by friction against them. Eddies are therefore set up as shown

collecting all the sand in their neighbourhood. The explanation appears to be that the wind exerts a shepherding effect. If the surface between the dunes is fairly smooth, the drag on wind there is less than it is along the edge of the dune. Eddies are thus set up which blow towards the dune, and so keep the intervening surface swept clean (Fig. 140).

[E.N.A.

(A) In the sand-sea of the Algerian Sahara

[U.S. Dept. of Interior

(B) In Death Valley, California. Cottonwood Mountains in the background

SAND DUNES

[E.N.A.

(A) The rocky waste of Ahmar-Kreddou, Sfa

[E.N.A.

(B) Kettle oasis in the Souf

IN THE ALGERIAN SAHARA
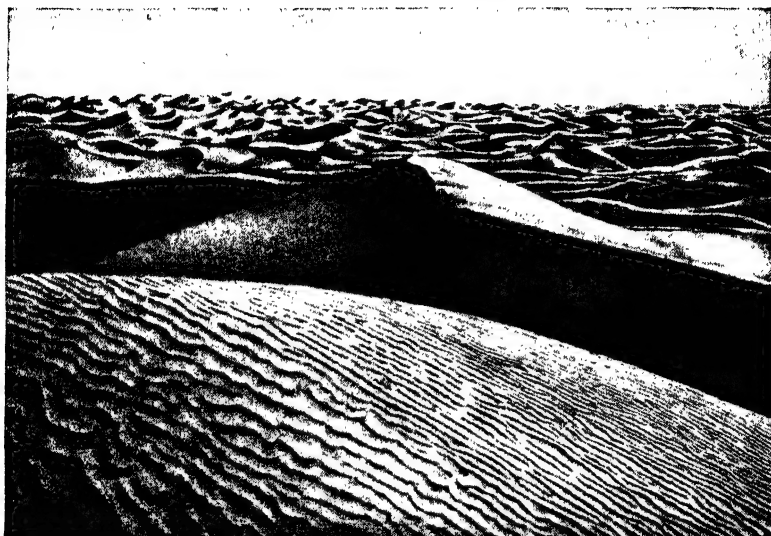
Fig. 141

A characteristic view of an Egyptian "sand sea." Drawn by M. V. Binosi. (*From W. H. Hume, "Geology of Egypt," Vol. I., by permission*)

In the great Egyptian Sand Sea (Fig. 141), however, another factor operates. Here the dunes, which include seifs in some parts, and colonies of irregular barchans in others, rise above a platform of coarse sand. This has accumulated around their bases because the grains are too large to accompany the finer sand which is carried up the slopes of the dunes. Wide, featureless sand sheets accumulate where the wind disperses chance mounds of sand, instead of developing them into dunes. Here the effect of sprinkled pebbles comes in. A pebbly surface increases the drag on the wind to such an extent that the velocity near the ground is less than it is over a patch of clean sand. The resulting eddies therefore blow from the patch towards the pebbly surface until the sand is again evenly distributed between the pebbles. Widespread sand sheets are also characteristically developed on the borders of deserts, where a scanty vegetation diversifies the surface

[*G. C. Gilbert, U.S. Geol. Survey*

FIG. 142

Desert scrub, with basalt-capped mesa behind, N.E. of The Solitario, Texas

(Fig. 142 and Plate 63B). Grass and scrub break the force of the wind and inblown sand is evenly distributed.

One of the most curious phenomena associated with dry dune sands is the mysterious booming which suddenly interrupts the silence in certain desert localities. Bagnold writes, " Native tales have woven it into fantasy ; sometimes it is the song of sirens who lure travellers to a waterless doom ; sometimes it is said to come upwards from bells still tolling underground in a sand-engulfed monastery ; or maybe it is merely the anger of the jinn ! But the legends, as collected by the late Lord Curzon, are hardly more astonishing than the thing itself. I have heard it in south-western Egypt 300 miles from the nearest habitation. On two occasions it happened on a still night, suddenly—a vibrant booming so loud that I had to shout to be heard by my companion. Soon other sources set going by the disturbance joined their music to the first. This weird chorus went on for more than five minutes continuously before silence returned." " Roaring " sands have

been described from a place in the Kalahari desert, where a long tongue of white sand is advancing across a red sandy plain. When the white sand is disturbed by walking or sliding down its steep face, the sand sets up a loud roaring, recalling the starting of an aeroplane engine. Despite much investigation and experiment no satisfactory explanation of the sounds is yet forthcoming. In some way an avalanching layer of sand sets all the grains vibrating together. An analogy is suggested by the sound given out when one corrugated book cover is drawn over another.

Loess

We must next consider what happens to the vast quantities of dust which have been winnowed from the desert sands and exported by the wind. From the deserts of Asia the wind carries the dust to the south and south-east over the grassy regions of China, where it is deposited and accumulated as a thick blanket of *loess* (Fig. 79). From the North African deserts much of the dust reaches the Atlantic, either directly or by way of the Congo basin, where it is retained for a time in the soil. Of the rest, some is trapped by the Mediterranean and Red Seas, while the balance is carried towards the steppes of Russia and Turkestan. Another very important supply of fine silt and dust was formerly provided by the rock flour of glacial deposits. During and after the retreat of each of the successive ice sheets, the finer material was sifted out by the wind and deposited over the steppe-like country outside the glaciated regions (Fig. 143). Thus it happens that a long belt of loess, mainly composed of glacial material in the west and of desert material in the east, stretches from France to China. The term *loess* comes from a town of that name in Alsace. Beginning as straggling belts of hills in France and Germany, the deposit becomes thicker and more extensive as it is traced across Russia and Turkestan, until in Shansi and the adjoining provinces of China it reaches its maximum development.

Loess is an accumulation of wind-borne dust and silt, washed down from the air by rain, and retained by the pro-

Fig. 143
Map showing the distribution in Europe of loess and loamy soil formed from loess (dotted), and its marginal relation to the last European ice sheet. (*After S. von Bubnoff*)

tective grip of the grasses of the steppe. Each spring the grass would grow a little higher on the material collected during the previous year, leaving behind a ramifying system of withered roots. Over immense areas many hundreds of feet have accumulated, whole landscapes having been buried, except where the higher peaks project above the blanket of loess. The material itself is yellow or light buff, very fine grained, and devoid of stratification. Although it is very friable and porous, the successive generations of grass roots, now represented by narrow tubes partly occupied by calcium carbonate, make it sufficiently coherent to stand up in vertical walls which do not crumble unless they are disturbed. The passage of traffic along country roads loosens the material, clouds of dust are removed by the wind, and the roads are worn down into steep-walled gullies and miniature canyons.

In the loess provinces of China rain and small streams carve the surface into a maze of ravines and badland topography (Plate 63A). The larger rivers flow in broad and fertile alluvial plains bordered by vertical bluffs. Here and in the lowland and deltaic plains to the east most of the alluvium is

simply loess redistributed by water. In the loess uplands cultivation of the slopes is made possible by terracing. The steep-sided cliffs and walls, whether natural or artificial, are often riddled with cave dwellings, many of which have their chimneys opening into the fields above. This mode of habitation has occasionally led to great disasters. In 1556, for example, widespread landslides and floods were started by a catastrophic earthquake and nearly a million peasants lost their lives.

In the semi-arid regions of the western States and in the Mississippi valley there are thick deposits of *adobe* which correspond in all essentials to the loess of Europe and Asia. Here again the material has been sifted by the wind from the rock waste of deserts and glaciated areas, and blown far outside the regions of supply, to find lodgment on surfaces, like the prairies, protected by vegetation. Similar deposits also occur in the pampas of South America.

Weathering and Stream Work in the Desert

The Sahara and the other sub-tropical deserts lie between the equatorial and temperate zones along belts of high atmospheric pressure where the prevalent descending winds are dry. The deserts of higher latitudes occur in regions where the rainfall is low either because of the great distance from the oceans (*e.g.* the Gobi of Central Asia) or because of the rain barrier interposed by high mountains near the coast (*e.g.* the deserts of N. and S. America). In all these arid regions the rainfall is rare and sporadic, both temperature and wind intensity are subject to violent daily and seasonal fluctuations, and vegetation is extremely scanty or entirely lacking.

Under these conditions mechanical weathering is dominant, involving the splitting, exfoliation, and crumbling of rocks by alternations of scorching heat and icy cold (Plate 23B). Nevertheless chemical weathering, though extremely slow, plays a far from negligible part. By decomposition and solution, rocks that would otherwise successfully resist the stresses set up by

temperature changes are gradually weakened until they can be shattered. By evaporation minute quantities of dissolved matter are brought to the surface. The loose salts are blown away, but oxides of iron, accompanied by traces of manganese and other similar oxides, form a red, brown, or black film which is firmly retained. The surfaces of long-exposed rocks and pebbles thus acquire a characteristic coat of "desert varnish."

Although most desert localities remain entirely unvisited by rain for years on end, no part can be regarded as permanently free from rain. Over a representative period of years the rainfall is limited to an average of a few inches per annum, 10 inches being the limit, reached only on the desert margins. In the adjoining semi-arid regions the annual rainfall rises to 10–20 inches, but even here long periods of drought are usual.

Evaporation far exceeds the rainfall in the desert. Permanent streams cannot originate under such conditions, although well nourished rivers, like the Nile, with adequate sources in humid regions, may cross the desert without entirely dwindling away. Outflowing streams are otherwise short and intermittent, and confined to coastal districts where, moreover, the rainfall is less scanty. The desert drainage is almost wholly internal, and directed towards the lowest parts of the many depressions which, owing to earth movements and wind erosion, characterise the desert surface. Evaporation prevents the growth of lakes from which, as in humid regions, the overflow could find an exit. The poetical generalisation that "the weariest river winds somewhere safe to sea" does not apply to arid regions.

The gorges and steep-sided wadis that dissect the uplands (Plate 62), the alluvial spreads that floor the depressions, and the salt deposits and other dried-up remains of ephemeral and vanished lakes all testify to the fact that running water as well as wind is concerned with the evolution of the desert landscape. Most of these features are an inheritance from Pleistocene times, when there were climatic oscillations involving periods of greater rainfall (Plate 63B). In the Sahara and Syria

occurrences of buried habitations, stone implements, and the fossil remains of trees of modern types all point to the comparatively recent prevalence of more genial conditions. Evidence for the more active flow of streams is found in the extinct " waterfalls " of certain wadis.

Despite the extreme desiccation of to-day, spasmodic stream action still continues. The chief characteristics of the rare desert rainstorms are their erratic distribution and brief duration, and—apart from occasional light showers—their intense violence. Houses of dried salt mud are washed away when a sudden " cloudburst " descends on an oasis, and travellers have been drowned in the floods that race down the dry wadis with little or no warning. Such torrents, swiftly generated in a distant upland rainstorm, carry a heavy load of mixed debris, prepared for them by years of weathering and wind erosion. Much of the load is dropped to form alluvial fans and "deltaic" deposits in front of the mountains or escarpments, as the carrying power is reduced by loss of gradient or by seepage. Choked by their own deposits the streams subdivide into innumerable channels and spread out laterally across the plain, which thus becomes covered with a veneer of fine sediment. If the rain falls over the gentle slopes of a depression a shallow sheet-flood may carry a mud flow towards the centre. If the water reaches the centre before it is lost by further seepage and evaporation a temporary lake is formed. There the dissolved material is concentrated by evaporation and finally deposited to form salt muds or glistening white sheets of rock salt, gypsum, and other salts. In western America the resulting alluvial plains are called *playas* and the more saline tracts are distinguished as *salinas* (Plate 85B). As only the finer debris is exported by wind, and salt-encrusted surfaces offer considerable resistance to ablation, the lowering of the surface by wind erosion is a very slow process which does not everywhere succeed in keeping pace with deposition.

If the alluvium increases in thickness it extends up the valleys and encroaches on the wind-swept and flood-washed rock slopes that lead up to the spurs and cliffs of mountains

and escarpments. So long as more material is brought in by streams than is removed by wind the depressions continue to be filled. It is doubtful whether this can happen in the heart of the desert, but it certainly takes place in semi-arid regions like the Great Basin (page 423), and it must have occurred in the present deserts when the rainfall was less scanty than now. In any case, the low swells between adjoining basins are sooner or later worn down, and the spreads of alluvium gradually extend from one depression to another, thus becoming united into still vaster plains.

A striking feature of desert and semi-arid landscapes is the sudden change of slope which is maintained as the edges of the uplands are worn back by erosion. The slopes of mountains and escarpments and the walls of the wadis are kept steep not only by wind abrasion at the base, but also because stream erosion, when it does occur, is mainly lateral. Near the heads of gorges and wadis the rare floods flush out the loose material and cut into the bedrock, but lower down the main channel is blocked by debris, and the outer distributaries, diverted to one side or the other, undercut the walls (Plate 62). Another effect which is locally important is that rain falling on a plateau of pervious rocks soaks through them and feeds intermittent springs at the foot of the bordering cliffs, which are thus again sapped away at their base. Meanwhile, the recession of the upper slopes is extremely slow, because disintegration is very slight compared with the effects of weathering in humid regions. Thus the typical wadis and desert gorges come to have broad flat floors and steep sides, rising in terraced steps to a vertical lip. Near their mouths they open out into alluvial fans which slope down to the plains. Between neighbouring wadis the plateaus rise by similarly abrupt cliffs and terraces, corresponding to the varied resistances of the truncated strata. In the absence of intervening soft beds, as in the tableland of the Gilf Kibir to the south of the Egyptian oases, the ascent may be by a single bold and precipitous escarpment. Between the cliffs and the feather edge of the alluvium there is generally a gently sloping rock surface for which the term *pediment* has been proposed.

By permission of the Egyptian Government] [*O. H. Little*

(A) Gorge of the Wadi Barud

By permission of the Egyptian Government] [*W. F. Hume*

(B) Wadi Gasab in the Plateau of Ma'aza

WADIS IN THE EGYPTIAN DESERT

[Capt. J. P. Koster

(A) "Badland" erosion of loess, Kansu Province, China

[W. C. Mendenhall, U.S. Geol. Survey

(B) Shore terrace of former lake, Colorado Desert, California

The Cycle of Erosion in Arid Regions

There is still considerable doubt regarding the relative importance of the effects of wind and water in the desert. As we have seen, there have been marked fluctuations of climate in the not very distant past, and certain desert features, such as the larger wadis and the extensive deposits of former lakes, could hardly have developed under the parching conditions of the present day. Such features are therefore shared by the landscapes of both desert and semi-arid regions. The following outline, though brief, will serve to indicate how the processes known to operate in the desert could ultimately reduce any given land surface to a desert peneplain.

The arid cycle may be supposed to begin on a region of uplands and depressions, determined, let us say, by earth movements. During the stage of *youth* each basin is separate from its neighbours. In the uplands short intermittent streams cut gullies and ravines which develop into wadis and canyons. The rock-waste is not carried off to the sea, but is spread over the depressions, turning them into sandy plains passing inwards into salt-cemented playas. By erosion the slopes of the uplands gradually recede, leaving narrow rock pediments in front, and the upper surfaces are slowly worn down. By accumulation of alluvium the basins are filled up. Consequently the general effect is towards levelling, although, as already pointed out, the contrast of cliff and plain never ceases to remain sharp. Moreover, offsetting the reduction of relief, new hollows are excavated by the wind, and dunes begin to grow and to migrate from the sources of sand supply.

The stage of maturity may be said to be reached when the lower basins begin to tap the higher ones by valleys which have extended headwards. The deposits of a higher basin may develop into typical badland topography as they are eroded away. Neighbouring basins thus gradually coalesce into more extensive ones which for the most part are almost perfectly flat plains, with tracts of mosaic pebble-pavement and vast sand wastes and chains of dunes. Meanwhile the uplands are dwindling away, and their remnants, flanked by outlying

buttes, rock towers, and pinnacles, rise abruptly from broadening pediments which slope down to the plains (Plate 64).

As the uplands are lowered the rainfall decreases still further, and less and less new material is contributed to the plains by running water. Wind action then becomes predominant. The general lowering of the surface by deflation and abrasion proceeds with little or no interruption by sheet floods and mud flows. This stage marks the beginning of *old age*. The shrinking uplands are worn back, leaving increasingly widespread pediments, diversified by clustered or isolated residual knobs and peaks, the most spectacular examples being the inselbergs developed from resistant masses of granitic and gneissic rocks. Until the cycle is interrupted by earth movements or a change of climate, wind erosion continues to lower the surface towards the base level fixed by the water table. And so the region is reduced to a peneplain of rock, desert pavement, and sand, the only breaks in the monotonous landscape—apart from barchans and seif dunes—being provided by residual domes and occasional steep-sided relics of the more persistent inselbergs.

The most remarkable examples of the old-age inselberg type of landscape occur in certain regions of Africa (*e.g.* Mozambique and Tanganyika territory) where the present climate is one of well marked wet and dry seasons. Precipitous, smoothly rounded peaks, isolated or in detached groups, rise boldly and abruptly above the forest, like islands above a sea of vegetation (Fig. 144). For this reason they have been called *inselberge* (island mounts). Other examples, only a little less spectacular, occur in the semi-arid regions of South-West Africa, Northern Nigeria (Plate 65A), and Western Australia, and in the Arabian desert, everywhere carved out of the more resistant granites and gneisses.

The surrounding plain or plateau is a more or less uplifted plain or plateau of the pediment type, with only a thin covering of soil, sand, gravel, or laterite, according to the nature of the present-day climate. An inselberg is clearly a special type of monadnock (page 189), but it differs from the latter, as developed in the humid cycle, in its astonishingly steep sides and
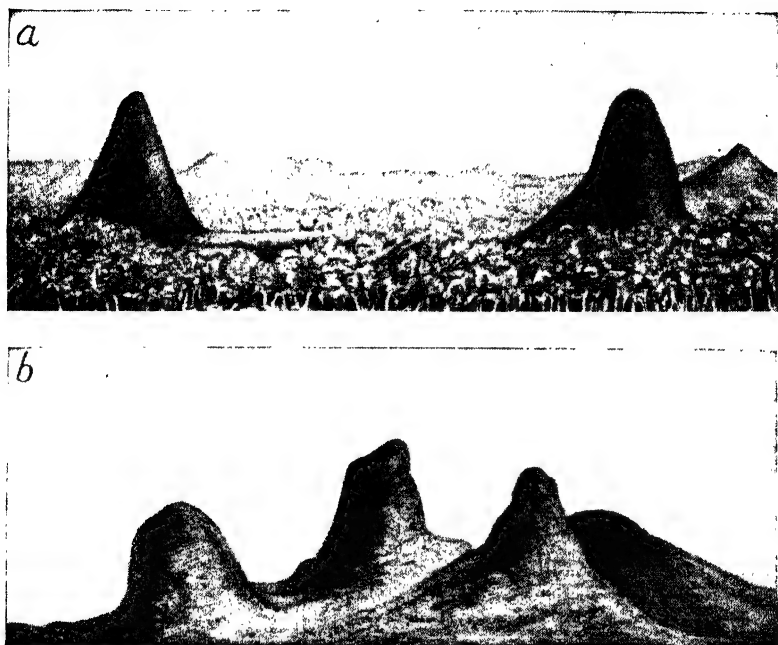
FIG. 144

Sketches of the inselberg landscape of Mozambique by E. J. Wayland :

(*a*) Koldwi, north of the Mtupa Pass, Ribawe

(*b*) Lebi, Mbulla Range (vegetation omitted)

in the abrupt transition—by way of a sharply concave bend—to the surface of the pediment. This contrast suggests that the inselberg landscape of eastern Africa may not have developed under present-day conditions, but is more likely to be an inheritance from a time when the climate was arid or semi-arid. Certainly the landscape is a very ancient one. In some coastal districts the pediment continues beneath a cover of Tertiary or Cretaceous sediments. There has therefore been ample time for a wide range of climatic conditions. Wherever the inselberg landscape is developed, a thick cover of younger formations must long ago have been removed from the old Pre-Cambrian crystalline rocks of which the inselbergs and the surrounding pediments are composed.

SUGGESTIONS FOR FURTHER READING

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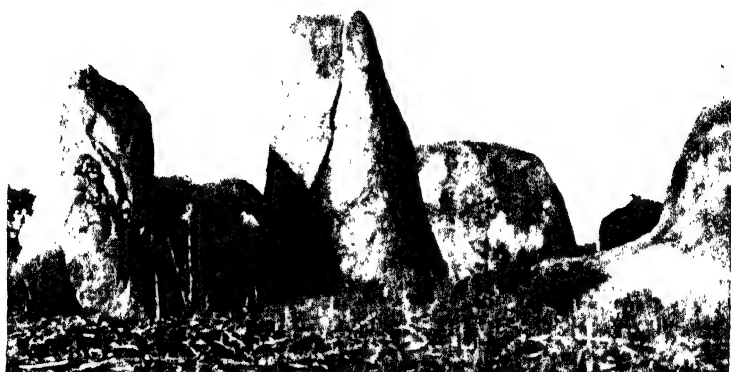
[*L.N.A.*

(A) Sandstone pillars, Tassili-des-Ajjar, Algerian Sahara

[*Dorien Leigh, Ltd.*

(B) Pillars of red sandstone, Monument Valley, Utah

EROSION RESIDUALS CONTROLLED BY JOINTING

[Dorien Leigh, Ltd.

(A) Stumpy finger-like inselbergs, Katsena, Zaria Province, N. Nigeria

[Dorien Leigh, Ltd.

(B) The Sugar Loaf, Rio de Janeiro, Brazil. An erosion residual of inselberg type

Chapter XIV

COASTAL SCENERY AND THE WORK OF THE SEA

Shore Lines

Nearly all coast lines have been initiated by relative movements between land and sea. A rise of sea level (see page 417), or a depression of the land, leads to the submergence of a landscape already moulded by sub-aerial agents. The drowning of a region of hills and valleys gives an indented coast line of bays, estuaries, gulfs, fjords, and straits, separated by headlands, peninsulas, and off-lying islands. Very broad bays, like the Great Australian Bight, result from the submergence of plains. Coasts that have originated in these ways are called *coasts of submergence.* Conversely, a fall of sea level or an elevation of the land and adjoining continental shelf leads to retreat of the sea and emergence of part of the sea floor. As the sea floor is essentially a realm of sedimentation its surface is generally smooth, and the resulting *coasts of emergence* have correspondingly simple, broadly flowing outlines. Other varieties of coast line include those determined by (*a*) volcanic activity; (*b*) faulting; (*c*) glaciation; and (*d*) the growth of coral reefs and atolls.

The general outlines of a newly formed coast are soon modified by marine erosion and deposition, with development of a wide variety of shore features and coastal scenery. By the incessant pounding of waves, which break up the rocks and wear back the cliffs, the sea cuts its way into the land like a horizontal saw. The liberated rock fragments are rounded by innumerable impacts and continual grinding as the line of breakers is carried backwards and forwards over the foreshore by the ebb and flow of the tide. The worn-down material is supplied to currents which dispose of it, together with all the products of land-waste brought in by rivers and glaciers and the wind. Much of the sediment is carried into deeper water before it comes to rest out on the sea floor, but some is drifted

along the shore by waves and currents, to form shoals and beaches, and to build up bars and spits wherever the transporting power is checked. Sheltered inlets thus barred off from the sea by long embankments of sand and shingle become silted up. In this and other ways (*e.g.* by the seaward growth of a delta) new land is added to the fringe of the old in partial compensation for the losses suffered elsewhere.

The waters of the seas and oceans readily respond by movement to the brushing of the wind over the surface ; to variations of temperature and salinity ; and to the gravitational attraction of the moon and sun (combined with the earth's rotation). The work of erosion, transport, and deposition carried out by the sea depends on the varied and often highly complex interplay of the waves, currents, and tides that result from these movements.

It may be noted in passing that lakes, especially the larger ones, behave in much the same way as enclosed seas. In consequence, the shore features of lakes and seas have much in common. A lake formed by obstruction (*e.g.* the lava-dammed Lake Kivu, p. 436) drowns the surrounding land and so acquires a shore line of the submergence type. A lake which has shrunk from its former extent in response to climatic or other changes (*e.g.* the Great Salt Lake of Utah, p. 424) is margined by flats and terraces of sediment (Plate 63B), and so acquires a shore line of the emergence type. Tides are negligible in lakes, but seasonal variations of rainfall may cause the water to advance and recede over a tract of shore which is alternately covered and exposed, though less frequently than the tide-swept foreshore of a coast. Waves and currents operate exactly as in land-locked seas of similar extent and depth, and are responsible for erosion and deposition on a corresponding scale. There are, of course, important biological contrasts. The swamps into which shallow lakes degenerate, with their luxuriant growth of aquatic vegetation and accumulations of peat, are very different from the mangrove swamps and tidal marshes that locally border the sea. On the other hand, lake shores have nothing to be compared with the coral reefs of tropical seas.

Tides and Currents

The tide is the periodic rise and fall of the sea which, on an average, occurs every 12 hours 26 minutes. Tides are essentially due to the passage around the earth, as it rotates, of two antipodal bulges of water produced by the differential attraction of the moon and sun. It is easy to understand that the water facing the moon should bulge up a little, but it is less obvious why there should be a similar bulge in the opposite direction on the other side of the earth. The basis of the explanation is that the water centred at A (Fig. 145) is attracted towards the moon more than the earth, centred at E, while the

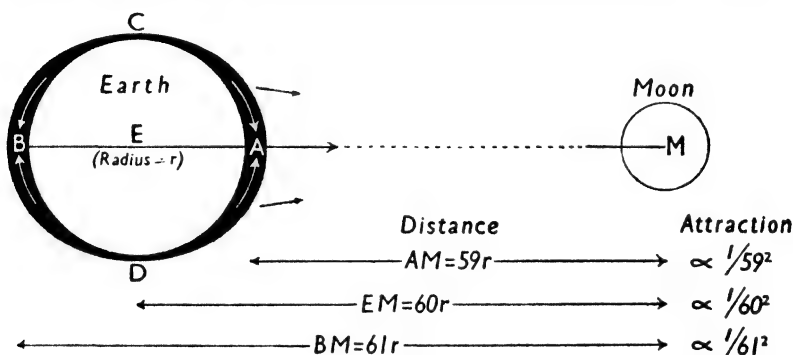



Fig. 145

Diagram to illustrate the generation of tides

earth, in turn, is attracted more than the water centred at B. The water at the far side is thus left behind to almost the same extent as the water on the near side is pulled forward. From places such as C and D the water is drawn away and low tide results. As the earth rotates each meridian comes in turn beneath the positions of high and low tide nearly twice a day; not exactly twice, because allowance must be made for the forward movement of the moon.

The effect of the sun is similar to that of the moon, but considerably less powerful. When the earth, moon, and sun fall along the same straight line, the tide-raising forces of sun and moon help each other, and tides of maximum range,

known as *spring tides*, result. When the sun and moon are at right angles relative to the earth, the moon produces high tides where the sun produces low tides. The tides are then less high and low than usual and are called *neap tides*.

In the open ocean the difference in level between high and low tide is only a few feet. In shallow seas, however, and especially where the tide is concentrated between converging shores, ranges of 20 to 30 feet are common and tidal currents are generated. A current of 2 miles an hour accompanies the inflowing tide as it advances up the English Channel. In the Bristol Channel the spring tides reach a height of 42 feet, and give rise to a current of 10 miles an hour. In extreme cases, such as the latter, where the tidal stream is crowded into the narrow end of a shallowing funnel, the water advances with a wave-like front of roaring surf which is known as a *bore*.

Near the shore inflowing tidal currents are often sufficiently powerful to move shingle and so to scour the bottom and transport sediment inshore or alongshore. The complementary outflowing currents of the ebb tide are less effective as eroding and transporting agents, because they start in shallow water and advance into deeper water. Pebbles and sand are left behind, and only the finer material is drawn back. In estuaries, where the outward flow of river water is added to the ebb current, transport is dominantly seaward. But since the fresh river water, carrying a load of silt and mud, tends to slide out over the heavier salt water which has crept in along the bottom, it is the upper suspended load that is mainly swept out to sea, while the coarser debris is stranded and tends to accumulate as sand bars.

Currents of a convectional type arise as a result of variations in the density of sea water, brought about to a very slight extent by heating in tropical regions and cooling in polar regions, but far more effectively by changes of salinity. Such changes depend on (*a*) inflow of rivers, rainfall, and the melting of ice, all of which freshen the water ; and (*b*) evaporation, which increases the salinity. The dissolved salts in sea water have the following average composition, corresponding to a salinity of 35 :

[*Fox Photos*

(A) Atlantic storm waves attacking granite cliffs, Scilly Isles

[*H.M. Geol. Survey*

(B) Recession of cliffs of glacial sands and gravels, 1936. South of Lowestoft, Suffolk

COAST EROSION

[*H.M. Geol. Survey*

(A) Cave and inlet development in cliffs of Old Red Sandstone. The Wife Geo, near Duncansby Head

[*H.M. Geol. Survey*

(B) Blow-hole or "gloup" due to collapse of roof of sea cave, The Devil's Bridge, Holborn Head

COAST EROSION, CAITHNESS

		Parts per 1,000	*Salinity in Particular Regions*	
Sodium chloride	$NaCl$	27·213	North Red Sea	41
Magnesium chloride	$MgCl_2$	3·807	Eastern Mediterranean	39
Magnesium sulphate	$MgSO_4$	1·658		
Calcium sulphate	$CaSO_4$	1·260	North Sea	34
Potassium sulphate	K_2SO_4	0·863	Near Greenland	31–33
Calcium carbonate	$CaCO_3$	0·123	Black Sea	18
Magnesium bromide	$MgBr_2$	0·076	Baltic Sea	2–8

Evaporation over the Mediterranean lowers its surface and increases the salinity and density. Surface currents therefore flow into the Mediterranean through the Dardanelles from the Sea of Marmora and the Black Sea (where the evaporation is more than neutralized by the inflow of rivers), and through the Straits of Gibraltar from the Atlantic (Fig. 146). In each

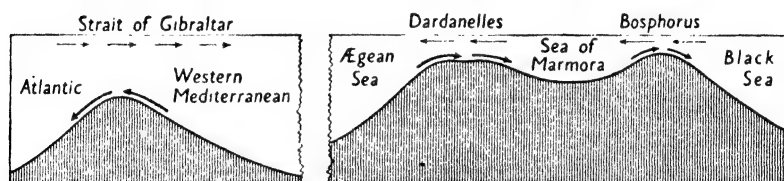



Fig. 146

Salinity currents of the Mediterranean and Black Seas. Water of low salinity (thin arrows) flows into the Mediterranean, and water of high salinity (thick arrows) flows out

case undercurrents of higher salinity flow outwards from the Mediterranean along the bottom. Shore deposits are affected by the surface currents, while in deeper water the floor is scoured by the bottom current. A similar interchange of water takes place between the highly saline Red Sea and the Indian Ocean, and also between the comparatively fresh Baltic and the North Sea. Since the less saline and lighter water always tends to spread over the more saline and heavier water, the surface current flows in all cases towards the region of higher salinity, while the bottom current is in the opposite direction.

The prevailing winds and the configuration of the continents determine the superficial but gigantic eddies which constitute the main currents of the oceans. These have noteworthy climatic and biological effects, but are otherwise of

little geological importance. In the vicinity of land, however, the currents due to wind drift contribute to the general movements responsible for shore-line processes.

Waves

Apart from tidal effects and accidental disturbances of the sea associated with earthquakes and volcanic eruptions, waves are entirely due to the sweeping of winds over the surface of the water. The surface is thrown into undulations which move forward and gradually increase in height and speed. The *height* of a wave is the vertical distance from trough to crest (C*a* in Fig. 148). The horizontal distance from crest

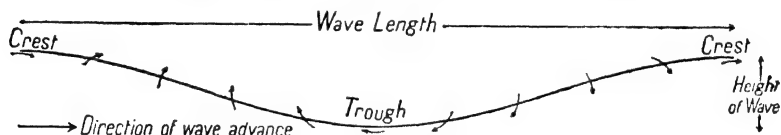



Fig. 147

Profile of a wave of oscillation from crest to crest, showing the directions of movement of water particles at various points

to crest—or from trough to trough—is called the *wave length.* The height ultimately attained by a wind-driven wave, where it is not restricted by shallowing water, depends on the strength, duration, and *fetch* of the wind, the fetch being the length of the open stretch of water across which the wind is blowing. When the loss of energy involved in the propagation of the waves through the water is just balanced by the amount of energy supplied from the wind, the height reaches its maximum. At this limit the height in feet is, numerically, roughly half the speed of the wind in miles per hour. In the open ocean heights of 5 to 15 feet are common, increasing to 40 or 50 feet in severe storms. The corresponding wave lengths range from 200 to 700 feet, and the speeds from 20 to 60 miles per hour. Waves may travel into regions of calm weather far beyond the fetch of wind in which they were generated, thus giving rise to a *groundswell.* The " free " waves of a groundswell gradually

flatten out relative to the "forced" waves of the high seas from which they spread, and wave lengths of 1,000 feet or more are then not uncommon.

It is important to realize that in the open sea—apart from wind drift—it is only the wave form that moves forward, not the water itself. Each particle of water moves round a circular orbit during the passage of each complete wave, the diameter being equal to the height of the wave (see Figs. 147–148). This is demonstrated by the behaviour of a floating cork under which a train of waves is passing. Each time the cork rises and falls it also sways to and fro, without advancing appreciably from its mean position. Such waves are called *waves of oscilla-*

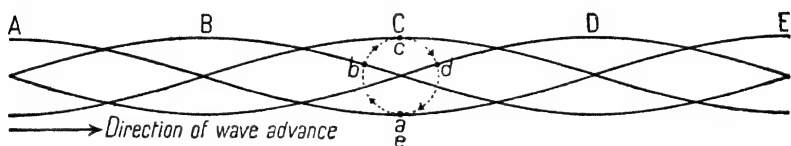



FIG. 148

Diagram showing the orbit of a water particle during the passage of a wave of oscillation. A, B, C, D, E mark successive positions of the crest ; *a*, *b*, *c*, *d*, *e* are the corresponding positions of the particle. AE = wave length ; C*a* = wave height

tion. If the wind is strong, however, each water particle advances a little farther than it recedes. Similarly, in shallow water, where friction against the bottom begins to be felt, each particle recedes a little less than it advances. In both cases the orbit, instead of being a closed circle, then resembles an ellipse which is not quite closed and the water therefore slowly drifts forward in the direction of wave advance.

When gusts of wind brush over a field of corn the stalks repeatedly bend forward and recover, and waves visibly spread across the surface. Here it is obvious that the wave motion is not confined to the surface, since it is shared by the stalks right down to the ground. In the same way the energy contributed by the wind to a body of water is transmitted downwards as well as along the surface. Owing to friction the diameters of the orbits rapidly diminish in depth until at a depth of the same order as the wave length they become

negligible. The greatest depth at which sediment on the sea floor can just be stirred by the oscillating water is called the *wave base*. In shallow seas and on the continental shelf, where the depth of water is less than this (*i.e.* less than about 600 feet), pebbles, sand grains, and mud particles can thus be kept moving until currents roll or waft them to depths where they remain at rest, undisturbed by wave action. Off Land's End stones up to a pound in weight are sometimes washed into lobster crawls at depths of 100 to 200 feet. Mud particles may even be kept on the move until they are quietly dropped over the edge of the continental shelf.

Agitation of the sea floor involves friction against the bottom,

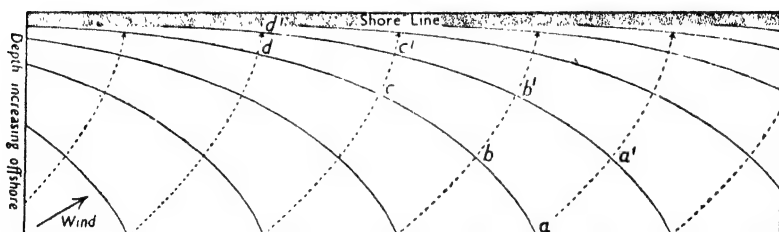



Fig. 149

Wave refraction. Diagram to illustrate the swing of oblique waves towards parallelism with the shore. While the crest at *a* advances to *a'*, the crest at *b* (in shallower water) advances a shorter distance to *b'*, and so on. The crest lines *abcd* thus become curved as shown

and in consequence, as the water shallows, the waves in front are retarded and the wave length decreases. For this reason, as a wave approaches a shore line obliquely its crest line swings towards parallelism with the shore, as shown in Fig. 149. The effect of wave retardation off an indented coast is illustrated by Fig. 150. The waves advance more rapidly through the deeper water opposite a bay than through the shallower water opposite a headland. Thus the crest of a wave at *a* moves to *a'*, while the crest at *b* moves only to *b'*. The waves thus become curved or *refracted*, again towards parallelism with the shore line. Consequently, when the shore is reached by a wave such as *a b c d e*, all the energy from the long stretch *ac* is concentrated on the headland AC (and that from *de* on DE).

In contrast, the very much smaller amount of energy from the short stretch *cd* is spread around the shores of the bay from C to D. Thus, while headlands are being vigorously attacked by powerful waves, the bays are not unduly disturbed and their waters provide safe anchorage for vessels sheltering from a storm. In the same way waves entering a harbour between the piers spread out and merely ruffle the water inside.

When a wave reaches the foreshore and enters water of which the mean depth is about the same as the height of the

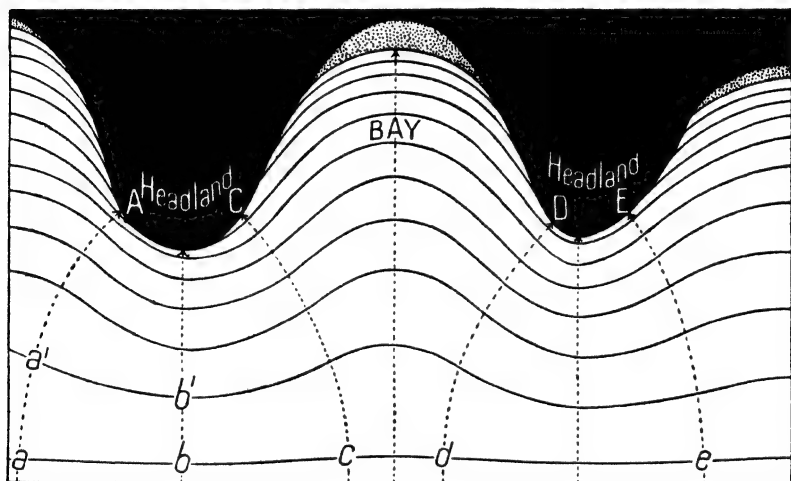



Fig. 150

Refraction of waves approaching bays and headlands, showing the concentration of wave energy against the headlands and its diffusion around the shores of the bays

wave, it becomes a *breaker*. The amount of water in front being insufficient to complete the wave form, while the orbital motion still continues, the crest is left unsupported and plunges over. The surface water then surges forward as a turbulent sheet of surf. The *wave of oscillation* has passed into a *wave of translation*. It is the bodily advance of the water in this kind of wave that makes surf-riding possible. The final *uprush* or *swash* on a shelving beach is followed by a *backwash*, as the water returns down the slope.

Surf waves pile up the water against the coast, and onshore

currents, especially the drift maintained by winds blowing strongly towards the shore, have the same effect. This tendency to raise the sea level is counterbalanced by a compensating current, called the *undertow*, which flows along the bottom away from the shore. The undertow is a pulsating current, becoming stronger under the wave troughs, where it is reinforced by the orbital motion of the water, and correspondingly weaker under the crests. It also tends to be concentrated along hidden depressions on the sea floor. The undertow is often a source of serious peril to bathers.

Marine Erosion

The sea operates as an agent of erosion in four different ways :

(*a*) by the *hydraulic action* of the water itself, involving the picking up of loose material by currents and waves, and the shattering of rocks as the waves crash, like giant water-hammers, against the cliffs (Plate 66A) ;

(*b*) by *corrasion*, when waves, armed with rock fragments, hurl them against the cliffs and, co-operating with currents, drag them to and fro across the rocks of the foreshore ;

(*c*) by *attrition*, as the fragments or " tools " are themselves worn down by impact and friction ; and

(*d*) by *corrosion*, *i.e.* solvent and chemical action, which in the case of sea water is of limited importance, except on limestone coasts.

The destructive impact of breakers against obstructions is often far greater than is generally realized. The pressure exerted by Atlantic waves averages over 600 lb. per square foot during the summer, and over 2,000 during the winter, while in great storms it may exceed even 6,000. Thus, not only cliffs, but also sea walls, breakwaters, and exposed lighthouses are subjected to shocks of enormous intensity. Cracks and crevices are quickly opened up and extended. Water is forcibly driven into every opening, tightly compressing the air confined within the rocks. As each wave recedes the com-

pressed air suddenly expands with explosive force, and large blocks as well as small thus become loosened and ultimately blown out by pressure from the back. The combined activity of bombardment and blasting is most effective as a quarrying process on rocks that are already divided into blocks by jointing and bedding, or otherwise fractured, *e.g.* along faults and crush-zones.

Cliffs originate by the undercutting action of waves against the slopes of the coastal land. By collapse of the rocks overhanging the notch which is excavated at the base of the cliffs, the latter gradually recede and present a steep face towards the advancing sea (Plate 68B). But where the cliffs are protected for a time by fallen debris, and especially if they are composed of poorly consolidated rocks, the upper slopes may be worn back by weathering, rainwash, and slumping. At any given place the actual form of the cliff depends on the nature and structure of the rocks there exposed, and on the relative rates of marine erosion and subaerial denudation. Since there are few stretches of coast along which the rocks are equally resistant, coasts are generally worn back with pronounced irregularities. Caves are excavated in belts of weakness and especially where the rocks are strongly jointed. By subsequent roof collapse and removal of the debris long narrow inlets develop. In Scotland and the Faroes such a tidal inlet (Plate 67A) is called a *geo* (" g " hard—Norse, *gya*, a creek). A cave at the landward end of a geo—or indeed any sea cave—may communicate with the surface by way of a vertical shaft which may be some distance from the edge of the cliff. A natural chimney of this kind (Plate 67B) is known as a *blow hole* or *gloup* (a throat). The opening is formed by the falling in of joint blocks loosened by the hydraulic action of wave-compressed air already described. The name *blow hole* refers to the fact that during storms spray is forcibly blown into the air each time a foaming breaker surges through the cave beneath.

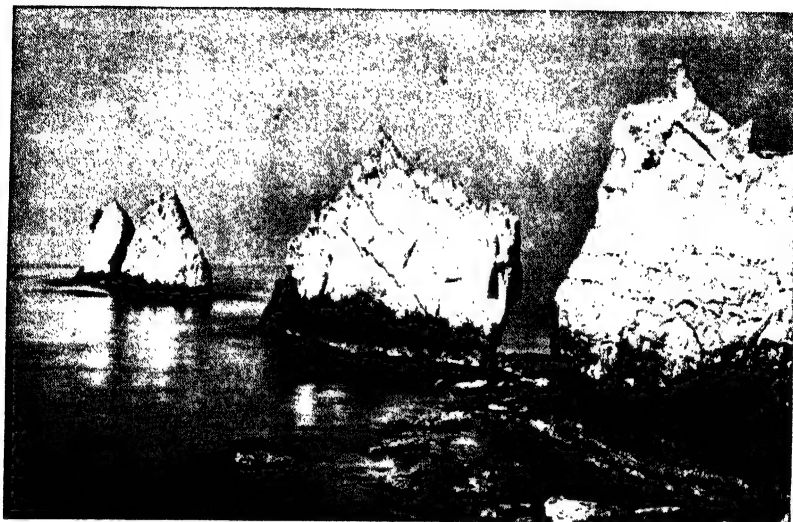
When two caves on opposite sides of a headland unite, a natural arch results, and may persist for a time (Plate 68A). Later the arch falls in, and the seaward portion of the headland then remains as an isolated stack (Plate 68B). Well known

[H.M. Geol. Survey

Fig. 151

The Needles, Isle of Wight. Stacks cut in Chalk

[H.M. Geol. Survey

Fig. 152

The Old Man of Hoy, Orkneys. A stack of Old Red Sandstone, 450 feet high, rising from a platform of lava on which the sandstone lies unconformably

[H.M. Geol. Survey

(A) Arch cut in Old Red Sandstone strata. The Needle Eye, near Wick

 [H.M. Geol. Survey

(B) Stacks and cliffs of Old Red Sandstone, Duncansby

COAST EROSION, CAITHNESS

[H.M. Geol. Survey

(A) Wave-cut platform cut across isoclinally folded Silurian strata, near St. Abb's Head, Berwickshire

[H.M. Geol. Survey

(B) Chalk cliffs, showing dry valleys left "hanging" by recession of cliffs. Wave-cut platform and shingle beach in front. The Seven Sisters, Sussex

COAST EROSION

examples of stacks are the Chalk pinnacles at the western extremity of the Isle of Wight known as The Needles (Fig. 151), and the impressive towers of Old Red Sandstone in the Orkneys, one of which, 450 feet high, is called the Old Man of Hoy (Fig. 152).

As the cliffs are worn back a *wave-cut platform* is left in front (Fig. 153), the upper part of which is visible as the rocky foreshore exposed at low tide (Plate 69). There may be patches of sand and pebbles in depressions, and beach-like fringes strewn with fallen debris along the foot of the cliffs, but all such material is continually being broken up by the waves and used by them for further erosive work, until finally it is ground down to sizes that can be carried away by currents.

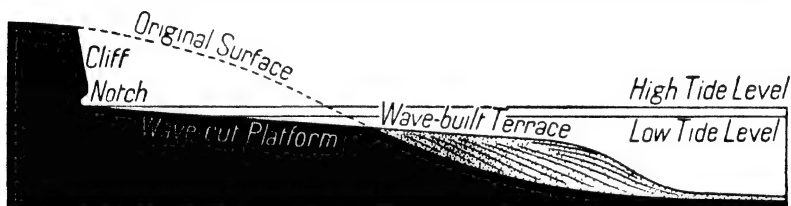



Fig. 153

Diagrammatic section showing a stage in the development of sea cliff, wave-cut platform, and wave-built shore-face terrace

While all this is going on the platform itself is being abraded as debris is swept to and fro across its surface. Since the outer parts have been subjected to scouring longer than the inner, a gentle seaward slope is developed. In massive and resistant rocks this is an extremely slow process. Consequently, as the cliffs recede and the platform becomes very wide, the waves have to cross a broad expanse of shallow water, so that when they reach the cliffs most of their energy has already been dissipated. Thus the rate of coast erosion is automatically reduced. In high latitudes, however, the cliffs may still continue to be worn back by frost and thaw, provided that the waves are able to remove what would otherwise become a protective apron of scree. The wave-cut platform off the rocky coast of west and north-west Norway—there known as the *strandflat*—has reached an exceptional width by this co-

S.W. N.E.

Fedje Fjord Fens Fjord

Igneous and Metamorphic Rocks Lindås Peninsula

Fig. 154

Section across the *strandflat* north of Bergen, Norway. Length of section 32 miles. (*After F. Nansen*)

operation of processes, locally up to as much as 37 miles. It now stands slightly above the present sea level (because of recent isostatic uplift) and innumerable stacks and skerries rise above its surface (Fig. 154).

On the other hand, if the sea is encroaching on a coast of

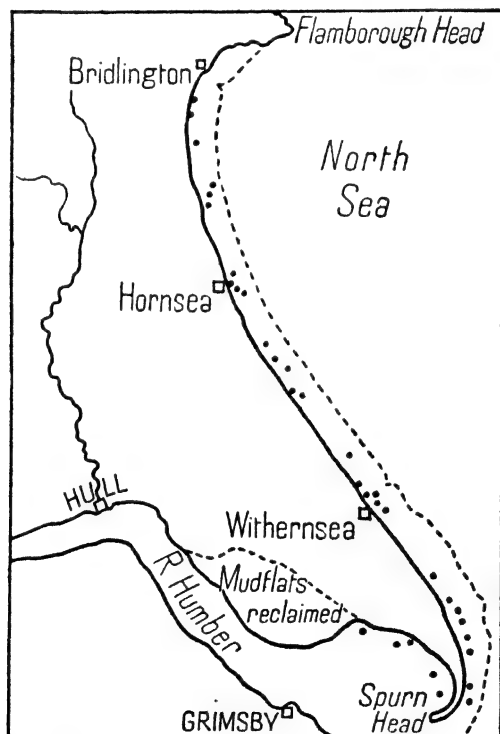



Fig. 155

Map showing the coast erosion and lost villages of Holderness since Roman times (*After T. Sheppard*)

poorly consolidated rocks, the platform in front is much more quickly abraded and normal coast erosion proceeds vigorously (Plate 66B). In some localities the inroads of the sea reach alarming proportions. The most serious loss of land in Britain is suffered along the Yorkshire coast south of Flamborough Head, where the waves have the easy task of demolishing glacial deposits of sand, gravel, and boulder clay. Since Roman times this 35-mile stretch of coast has been worn back $2\frac{1}{2}$ or 3 miles, and many villages and ancient landmarks have been swept away (Fig. 155). During the last hundred years the average rate of cliff recession has been 5 or 6 feet per year. The rate is not uniform, however, for severe storms and localized cliff falls do more damage in a short time than is otherwise accomplished in several average years.

The Profile of Equilibrium

In appropriate circumstances some of the sediment in transit across the wave-cut platform accumulates in the deeper water beyond, to form a *shoreface terrace* which grows forward like a broad embankment with its upper surface in smooth continuity with the platform. The combined shore and off-shore surface in this case, as in others, is a product of the joint action of erosion and deposition, each of which varies considerably from time to time and from place to place. The supply of sediment, for example, is irregular both in rate and distribution, since contributions are received from rivers and currents as well as from cliff wastage and platform abrasion, all fluctuating sources of income. The processes concerned in the removal of sediment—also widely variable—are themselves largely controlled by the slope of the shore and its seaward continuation—that is to say, by the profile of the surface taken at right angles to the shore. A relatively steep slope favours removal of sediment from the landward side, so that the slope becomes less steep. Conversely, a relatively gentle slope favours beach deposition on the landward side, so that the slope becomes steeper. The surface is therefore being

continually modified, and in such a way that at each point it tends to acquire just the right slope to ensure that incoming supplies of sediment can be carried away as fast as they are received. When the profile is so adjusted that this state of balance is achieved, it is called a *profile of equilibrium.*

For every set of conditions there is an appropriate profile of equilibrium and, as the conditions vary, so the actual profile is modified to keep pace with them, generally by fluctuations about an average which is fairly stable.

Along a shore of submergence the slope of the initial surface may be either steeper or gentler than that of the ideal profile of equilibrium. Suppose AB in Fig. 156 represents a steep initial slope. In transforming this into the profile of equilibrium CD, the waves cut a cliff-backed platform and

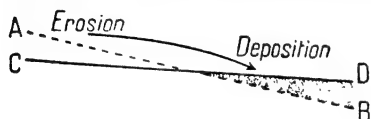



FIG. 156

The development of a profile of equilibrium CD from a more steeply sloping initial surface, AB

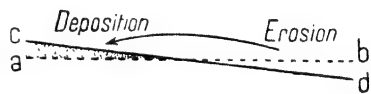



FIG. 157

The development of a profile of equilibrium *cd* from a more gently sloping initial surface, *ab*

wear it down by abrasion, and the resulting sediment is deposited as a shoreface terrace, as already illustrated in Fig. 153. If conditions then change so that the profile already in existence (*ab* in Fig. 157) is less steep than the new profile of equilibrium *cd*, then the platform is built up by deposition of sediment. Thus it commonly happens that a wave-cut platform is partially or wholly covered with a veneer of beach material.

Next, suppose *ab* represents an initial slope that is relatively gentle—as when a broad valley becomes a bay by submergence. In transforming this into the profile of equilibrium *cd*, waves and currents build up a beach around the shores of the bay. Initial surfaces that may be almost flat are provided by the drowning of extensive alluvial plains, and on a still more widespread scale by uplift of the sea floor. In these cases, as described on page 304, barrier beaches, called *offshore bars,* begin to develop far from the ill-defined mainland, and loose

[*Aerofilms, Ltd.*

(A) A bay scooped out by the sea, Lulworth Cove, Dorset (see also Plate 7)

[*Aerofilms, Ltd.*

(B) Beach drift impeded by groynes, St. Margaret's Bay, Isle of Wight

I. C. Russell, U.S. Geol. Survey

(A) Hook or recurved spit, Duck Point, Grand Traverse Bay, Lake Michigan

 [*H.M. Geol. Survey*

(B) Chesil Beach, viewed from the West Cliff, Portland, Dorset

sediment from the sea floor is driven landwards. As the waves lose energy the sediment is deposited long before the shore is reached, and thus the submarine foundations of an *offshore bar* are laid. The further development of these constructions is described on pages 304–6).

Transport and Deposition Transverse to the Shore

Leaving the longshore drift of sediment to be considered later, let us now review the actual processes that control the seaward and landward migration of beach and terrace material.

In bays where the initial slope is gentle, the landward currents due to translatory waves and inflowing tides are at first more effective on balance than the weak seaward currents due to undertow and outflowing tides (*cf.* page 286). A beach is therefore built up to the equilibrium profile. The most obvious landward movement is seen when the uprush of a breaker sweeps a mixed assemblage of sediment up the beach. Some of the coarser material, often including cobbles and pebbles, is left stranded at the top, while the rest is dragged back by the backwash. Storm waves at specially high tides thus build up a coarse *storm beach* well above the reach of ordinary waves and tides. Once the beach profile is adjusted to average conditions any additional supplies of sediment are removed, either by seaward currents (which now have the advantage of gravity owing to the steepened slope) or, when the sand is dry, by wind.

If the prevailing winds drive the beach sand landwards to form a belt of sand dunes, the profile is restored by compensating additions from the sea floor. Such landward migration is convincingly demonstrated by the existence of beaches and dunes that are largely composed of ground-up shells that could only have come from the sea floor. Excellent examples occur at St. Ives and Perranporth along the north-west coast of Cornwall.

The undertow, assisted by outflowing tides, carries sand and finer sediment seawards, and very large quantities may be scoured away from the beach when onshore gales raise the

head of water against the coast, and so maintain a powerful undertow. During such storms beaches become thinned and considerable patches may be entirely removed for a time. But gradually the beaches are built up again, restored by waves and currents, including shoreward undercurrents set up by offshore winds which lower the head of water against the coast. Beach growth is thus particularly favoured by gales blowing offshore. It should be noticed that the hydraulic currents along the sea floor always transport material in the direction opposite to that of the wind.

Interference with the natural profile by offshore dredging may increase the undertow to such an extent that the beach is withdrawn until the artificial depression is filled up. In 1896, for example, dredging was started off the coast north of Start Point to furnish shingle for use in the harbour works at Plymouth. As a result the beach at Hallsands began to disappear, cliff erosion became an ever-increasing menace, and in 1917 the village itself was washed away.

Off headlands the sea floor often shelves comparatively steeply to begin with and the seaward currents are the more effective ones from the start, a strong undertow being favoured both by wave concentration and gravity. Figs. 153 and 156 illustrate the results. The boulders and large pebbles that remain for a time under the cliffs are steadily reduced in size until they are sufficiently ground down to be removed. A shingle beach is simply a transitional stage through which the larger fragments of cliff debris must pass before beginning their seaward journey.

Ultimately the offshore slopes, though fluctuating from time to time, everywhere become adjusted into approximate equilibrium with the locally prevailing conditions. There is then a slow seaward migration of material at the expense of the wasting land. The transitory coarser debris is concentrated against the land, while the finest particles are swept out to sea, with much to-and-fro movement on the way, until each in turn passes beyond the range of wave and current action and finds a resting-place, either by burial or by being swept over the edge of the continental shelf. There is always

a tendency for some of the material to be carried to a depth from which it cannot be returned, because gravity assists the outward and hinders the inward movements. Moreover, the currents and wave oscillations rapidly weaken as the depth of water increases. It therefore follows that for each intermediate depth on the continental shelf there is a particular size of particle that is just too large to be returned landwards. Thus, during the outward migration of grains and particles of varied sizes, each size in turn, from large to small, tends ultimately to come to rest. There is inevitably a certain amount of overlapping of sizes, owing to variations of movement along the sea floor, and also because at any depth finer particles may be trapped in the interstices of the coarser material, so that sorting is never quite perfect. But with this reservation the sediments on the sea floor are found to become finer and finer as the depth increases ; the full outward sequence being boulders, cobbles, and pebbles ; coarse, medium, and fine sands ; and mud. The corresponding consolidated rocks are conglomerates, sandstones, and shales or mudstones.

Transport and Deposition along the Shore

Longshore drift of sediment is brought about in two ways : by beach drifting, due mainly to oblique waves, and farther out, by transport due to longshore currents. When waves are driven obliquely against the coast by strong winds, debris is carried up the beach in a forward sweeping curve. The backwash may have a slight forward movement at the start, owing to the swing of the water as it turns, but otherwise it tends to drag the material down the steepest slope, until it is caught by the next wave, which repeats the process (Fig. 158). By the continual repetition of this zig-zag progress sand and shingle are drifted along the shore.

The direction of drifting may vary from time to time, but along many shores there is a cumulative movement in one direction, controlled by the prevailing or most effective winds. A subsidiary factor which aids or hinders beach drifting is the

direction of the advancing flood tide. Some of the transported material dropped before or during the slack at high tide is not carried back again by the sluggish beginnings of the ebb-tide current. Farther out from the shore, wherever the general configuration of the coast is favourable, oblique winds and waves co-operate in generating intermittent and fluctuating longshore currents which again may be strengthened or weakened by the set of the tides. Thus longshore drift is by no means confined to the immediate shore line.

In the English Channel the dominant winds and the advancing tides both come from the south-west, and the prevailing direction of drift is therefore up channel. Along the east coast the drift is mainly southwards, as there the effective winds are

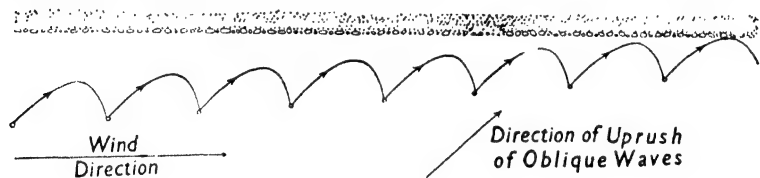



FIG. 158

Diagram to illustrate beach drifting, showing the path along a sloping beach, followed by a pebble under the influence of the uprush and backwash of successive oblique waves during an advancing tide

from the north-east, and the flood tide advances from the north. Wherever it is deemed desirable to protect the coast by checking the drift of sand and shingle, barriers, known as *groynes*, are erected across the beach. On the windward side of a groyne the debris is heaped up, while from the lee side it is washed away, to be retained in turn by the next groyne (Plate 70B). The groynes as a whole interrupt the natural flow of material necessary to maintain the beaches farther along the coast. Where the beaches are starved and drift away, as a result of artificial interference with the balance of deposition and erosion elsewhere, the coast is exposed to more vigorous wave attack. Thus to the east of such places as Brighton and Worthing the wastage of the cliffs has seriously increased since the groynes were built to protect these resorts.

When shore drift is in progress along an indented coast,

spits and bars are constructed as well as beaches. Where the coast turns in at the entrance to a bay or estuary the material transported by beach drift and longshore currents is carried more or less straight on and dropped into the deeper water beyond. The shoal thus started is gradually raised into an embankment. This grows in height by additions from its landward attachment until a ridge of sand or shingle is built above sea level in continuity with the shore from which the additions are contributed. The ridge increases in length by

Fig. 159
Diagram to illustrate the development of a hooked spit by the refraction of oblique waves

successive additions to its end, until waves or currents from some other quarter limit its forward growth.

If the ridge terminates in open water it is called a *spit.* Storm waves roll material over to the sheltered side, especially when they approach squarely, and some spits thus tend to migrate landwards, often becoming curved in the process. Curvature is also brought about by the tendency of oblique waves to swing round the end (*i.e.* to be refracted) in places where the sea floor beyond shelves rapidly into deeper water. A spit may thus be developed into a *hook*, as indicated in Fig. 159. Cross currents may assist or modify hook formation,

but it is clear that they cannot be essential, for hooked spits are equally characteristic along the shores of large lakes where tides are absent and currents are negligible (Plate 71A).

A good example of a curved spit is Spurn Head (Fig. 155), which extends into the Humber in stream-lined continuity with the Holderness coast. The latter is almost everywhere fringed with sand and shingle that drifts steadily from north

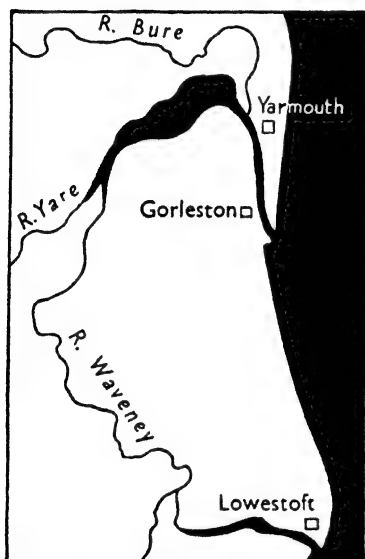



Fig. 160
River Yare, Norfolk

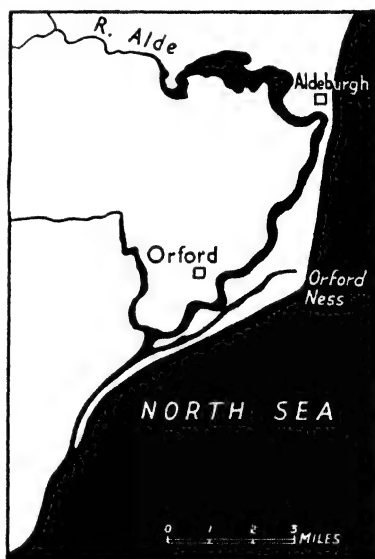



Fig. 161
River Alde, Suffolk

Examples of river deflection and extension in East Anglia by the southerly growth of sand and shingle spits. (Both drawn to same scale)

to south, fresh supplies being constantly furnished by the rapid erosion of the coast. Most of the transported material is carried beyond Spurn Head, cumbering the estuary with shoals on its way towards the Lincolnshire coast, where it is added to the seaward-growing coastal flats.

Southward drift is also very active along the east coast of Norfolk and Suffolk. Ten centuries ago the Yarmouth sands had already spread across the estuary of the Yare, forming an

obstruction which was largely responsible for the silting up of the Broads. About the year 1016 a barrier spit began to grow to the south, hugging the coast as closely as possible, and the river, diverted into a channel between the mainland and the spit, was obliged to extend itself southwards. By 1347 the end of the spit and the outlet of the river had reached Lowestoft. Since 1560, however, an artificial outlet has been maintained at Gorleston, where the spit now terminates, since the rest of it has long ago drifted south (Fig. 160). At Aldeburgh

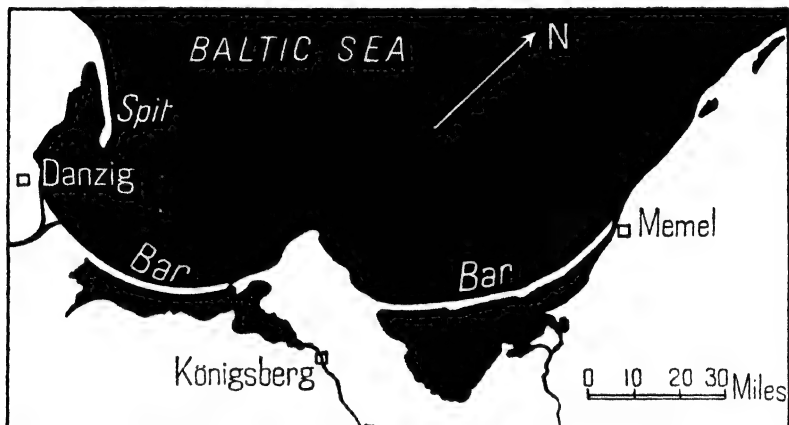



Fig. 162
Spits and bars along the south coast of the Baltic

the longest spit on the east coast has similarly diverted the outlet of the River Alde (Fig. 161).

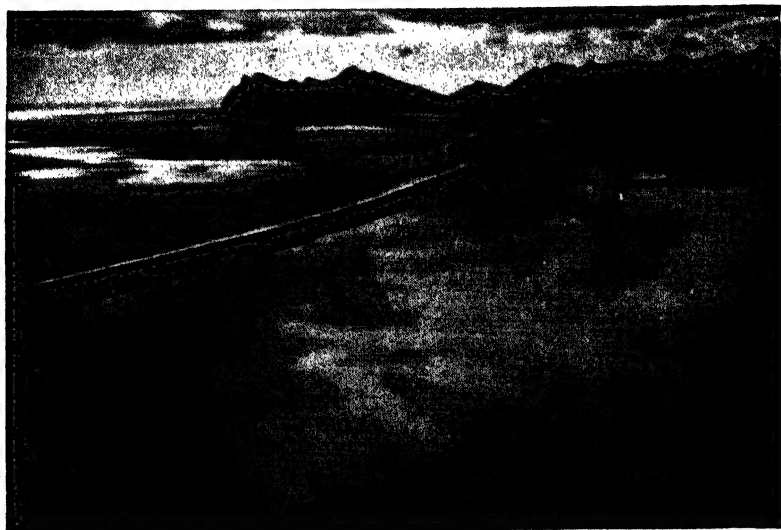
A *bar* is a spit which extends from one headland to another, or nearly so. If the bay inside is completely enclosed it becomes a shore-line lake. More usually, however, a narrow channel is kept open by tidal scour and outflowing drainage. Between Danzig and Memel, on the south Baltic coast, there are two very long bars, surmounted by sand dunes, with extensive tidal lagoons, called " haffs," on the landward side (Fig. 162). A beautiful example of a bar in Iceland is illustrated in Fig. 163. A similar construction of sand or shingle connecting a headland to an island, or one island to another, is a *connecting bar* or *tombolo* (Italian).

[*L. Hawkes*

FIG. 163
Bar, 10 miles long, across Lon Bay, Iceland

By far the most impressive shingle bar in Britain is Chesil Beach (Fig. 164). For six miles south-east of Bridport the Beach fringes the shore. Near Abbotsbury the shore recedes and for the next eight miles the Beach continues in front of the tidal lagoon of the Fleet as a bar well over 20 feet in height. Finally it crosses two miles of sea to the " Isle " of Portland, which is thus tied to the mainland. Chesil Beach is a composite structure, its shingle having accumulated from local sources as well as by drift from each end. At the north-west end there are pebbles of rocks from Cornwall and Devon ; at the south-east end much larger pebbles have been supplied from the Portland promontory (Plate 71B), where the beach drift is northwards ; while between these extremities the pebbles are relics from the land, now eroded away, that formerly stretched in front of the Fleet. Although towards the Portland end the Beach rises to the quite exceptional height of over 40 feet, the sea sometimes bursts over it during great storms and pours through breaches into the low-lying area

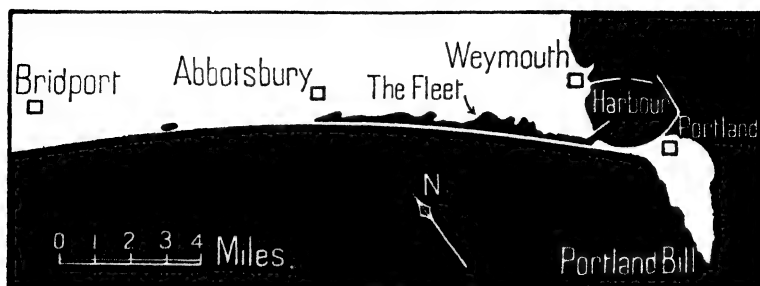



FIG. 164
Map of Chesil Beach, Dorset

beyond. Since two villages were demolished in 1824, the worst disaster of this kind occurred late in 1942, when the railway between Portland and Weymouth was partly washed away and the lower parts of Portland itself were seriously flooded.

SHORE LINES OF SUBMERGENCE

At the present day shores of submergence are the commonest types, because of post-glacial changes in sea level. Although many coasts are actually of compound origin, partial recovery from former submergence being indicated by raised beaches (Plate 6), on balance they still remain partially drowned. Moreover, the occurrence of buried forests locally demonstrates a quite recent phase of submergence. If a future change of climate led to the melting of the ice sheets of Greenland and Antarctica still further submergence would result.

Along coasts of " Atlantic " type, that is, where the trend lines of an orogenic belt are transverse to the coast, drowning gives an alternation of long promontories and estuaries. The latter are called *rias*, the name given them in Spain, where they occur south of Cape Finisterre. The south-west coast of Ireland (Cork and Kerry) is a perfect example of this type (Fig. 165). Along drowned coasts of " Pacific " type, where the structural grain is parallel to the coast, long islands and inlets following the trend lines are characteristic, as exemplified by the Dal-

matian coast of the Adriatic (Fig. 166). Where deeply cut glaciated valleys have been invaded by the sea after the melting of the glaciers a *fjord* type of coast results (Fig. 117), as described already on page 224.

The first effect of marine erosion on a newly formed coast of submergence is often to intensify all the initial irregularities of outline. Where the rocks vary in structure and resistance the waves pick out all the differences. Soft and fissured rocks

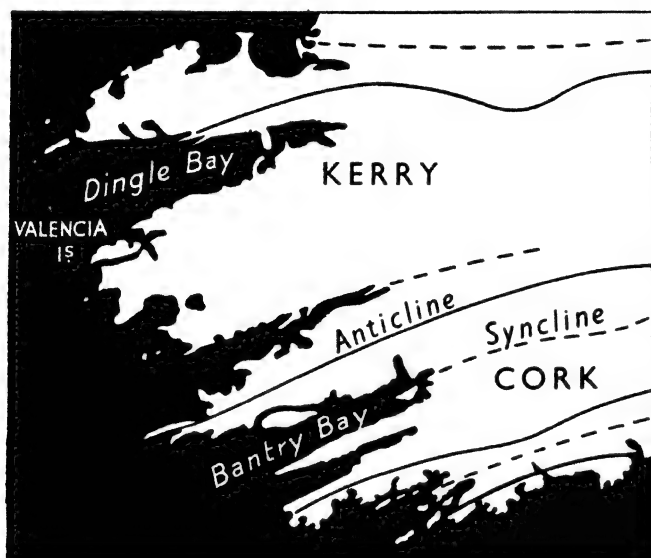



FIG. 165
Atlantic type of coast, south-west Ireland

are worn back into coves and bays, while the harder and more massive rocks stand out conspicuously. The Dorset coast north-east of Portland shows this process in active operation. Here there is a long coastal strip of soft Lower Cretaceous beds, backed on the landward side by an upland of Chalk, and formerly protected from the sea by a continuous rampart of hard upfolded Jurassic limestones. The sea has breached the latter in places and scooped out the softer rocks behind. The Stair Hole (Plate 7) illustrates the breaching stage, and Lul-

worth Cove (Plate 70A) is a beautiful example of a scooped-out bay.

Eventually, however, erosion and deposition co-operate to smooth out all the intricate outlines of a youthful shore line. As the headlands recede before the concentrated attack of the waves the stretches of cliffs become longer and straighter. Spits and bars bridge across the bays and inlets, and gradually encroach upon them as they keep in line with the retreating

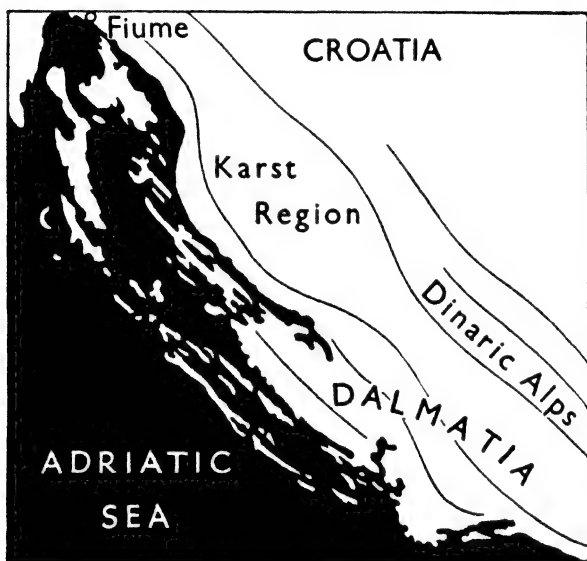



FIG. 166
Pacific type of coast, Yugoslavia

cliffs. Thus protected, the embayments are shoaled up by additions from streams on the one hand and from wind-blown sand on the other, until with the aid of salt-marsh vegetation the coast is built out to coalesce with the outer beach and its sand dunes. A coast of smoothly flowing outlines is thus evolved. Thereafter the shore line continues to retreat as a whole, and finally all signs of the original embayments may be obliterated, at which stage the lengthening cliffs become continuous (Plate 69B).

The barrier reefs and atolls of warm seas where corals

flourish are constructions which have been built up under conditions of submergence. Coral reefs, however, are products of life and are more appropriately dealt with in the next chapter.

Shore Lines of Emergence

Typical shore lines of emergence are not common at present, because they require uplift to an extent sufficient to overcome the effects of submergence due to recent changes of sea level. Finland, for example, is steadily rising isostatically, and the south and south-west coasts are fringed with tens of thousands of islands as a result of the emergence of the higher parts of a hummocky ice-moulded surface. But although this archipelago owes its existence to emergence it is merely part of a drowned land surface that is now less drowned than formerly.

A really typical shore line of emergence is one in which the sea floor with its veneer of sediments has been uplifted to form a nearly flat coastal plain with a smoothly flowing shore line margined by widespread stretches of shallow water. The Atlantic and Gulf coasts of the south-eastern United States and the Argentine shore of the River Plate are of this type. In accordance with the principle illustrated in Fig. 157 loose sediment from the sea floor is driven landwards in the process of restoring a profile of equilibrium. But here the waves may begin to drag the bottom many miles from the low-lying mainland. As the waves lose energy in crossing the shallows, much of the sediment is deposited long before the shore is reached, and thus the foundations of a *barrier beach* or *off-shore bar* are laid. How these constructions come to have their heads raised above water (Fig. 167) is not yet clearly established. An ordinary storm beach is formed at the upper landward limit reached by the waves. But as soon as a growing off-shore bar has reached a certain level it is swept by breakers, and material is then simply transferred from the outer to the inner side. The bar thus advances towards the shore like a submarine sand dune, and it cannot become other than a sub-

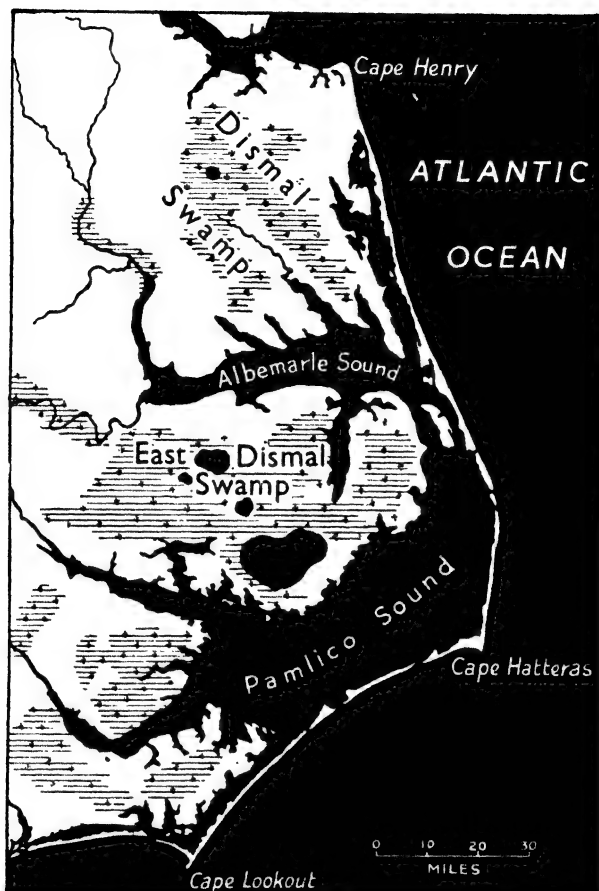



Fig. 167

Barrier beaches and swamps along the coast of North Carolina

marine feature until some other constructive factor begins to operate.

This additional factor is probably beach drifting. According to this view (which still requires to be verified by observation) one stretch of a migrating off-shore bar soon reaches an outward bulge of the coast, and is there constructed into an ordinary beach. From this point one arm of the bar can then be built above sea level like a lengthening spit, until it reaches

the next bulge of the coast and becomes a complete barrier beach, stretching across a broad shallow embayment which thus becomes a *lagoon.* The bar may be breached occasionally by storm waves, but any such break is sooner or later repaired by later drift.

Where the bar is in contact with the coast, the latter is eroded back and the bar, being tied to it, continues to encroach on the lagoon. Meanwhile, the lagoon itself is silted up with material thrown over the bar by the waves and brought in at the head from the land, until it becomes a salt marsh with a seaward belt of sand dunes. Eventually all these features continue to be cut back by the sea and a nearly straight beach-fringed coast is developed. The famous beaches of Daytona, Palm Beach, and Miami in Florida are off-shore bars which are now nowhere far from the land and in many places make contact with it.

Submarine Canyons

More than half a century ago it was discovered by soundings that the Hudson and Congo valleys continue over the sea floor as submarine trenches which interrupt the supposedly featureless floor of the continental shelf and become comparable in their dimensions with deep canyons where they traverse the continental slope beyond. One hundred and twenty miles south-east of New York the Hudson submarine canyon is now known to be 50 miles long, 6 miles across from rim to rim, and 3,700 feet deep (measured from the rim). The Congo example is on an even vaster scale. These submarine canyons were naturally a source of great perplexity, and as other examples came to be found elsewhere the mystery of their origin presented geologists with a challenge of increasing urgency.

About 1930 sounding ceased to be a slow and tedious process with the invention of an instrument that makes it possible to measure the depth by timing the interval required for a sound to reach the sea floor and to be reflected back as an echo. Since then detailed explorations of the sea floor by

echo sounding have been actively carried out in a number of selected but widely separated regions. Although less than one per cent. of the continental shelf and slope has so far been systematically surveyed in this way, more than a hundred submarine canyons have already been accurately charted. They occur off coasts of all kinds, and every continent provides examples, except Antarctica, the margins of which have not yet been tested. Some are in line with great rivers, but far more begin on the continental shelf, often far out, without relation to the drainage from the land, and all of them become features of vigorous relief on the steeper surfaces of the conti-

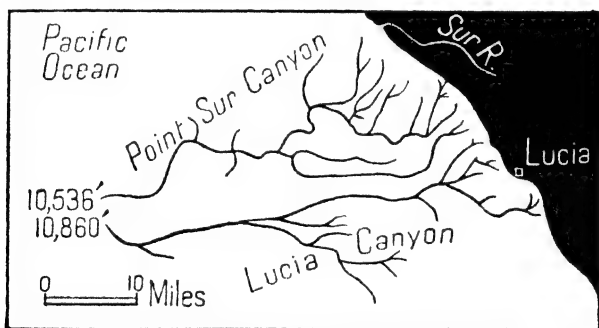



Fig. 168
Chart of the submarine canyons off the Californian coast between San Francisco and Los Angeles, showing the maximum depths to which they have been explored

nental slope, which thus turn out to be far more rugged than anyone could have suspected. A dendritic system of tributary valleys, as illustrated in Fig. 168, is characteristic. The resulting submarine topography closely resembles that of a land surface dissected by river erosion. The main canyons are broad, steep-sided, V-shaped gashes excavated in the sea floor to depths of as much as 4,000 feet below the rim. Some examples have been traced to depths of over 10,000 feet below sea level, but their terminations on the deep ocean floor still remain unfathomed. Samples dredged from the walls show that these amazing canyons are geologically quite young. Pliocene marine beds have been cut through and a coating of fresh mud suggests that at least some of the canyons are now

being filled rather than excavated. It is therefore probable that the canyons originated during Pleistocene time. But how?

The canyons must have been formed either above or below the sea. If above, then either the sea floor must have been raised or the sea level must have fallen by at least 10,000 feet. Each of these alternatives is equally preposterous. There is not the slightest evidence that any of the coasts concerned were pushed up a couple of miles and then restored to their present positions shortly afterwards, and the idea that this could have happened all over the world is purely fantastic. Lowering of the sea by 10,000 feet would imply that about thirty times as much water was precipitated on the lands in the form of continental ice sheets as we have any right to assume. The actual lowering of sea level during the glacial epochs was of the order 300 feet, an estimate that is confirmed by the depths of the lagoons of coral atolls and barrier reefs (p. 328). Thus we are driven to consider the only remaining possibility : that the canyons were formed under the sea, presumably by the erosive effects of some kind of submarine current.

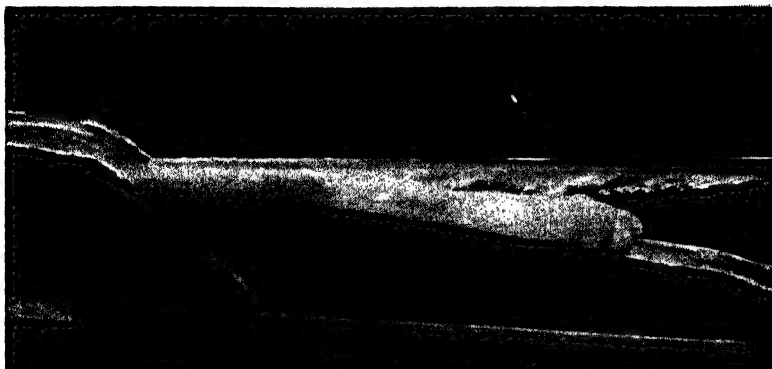
Among the many hypotheses that have been proposed to account for submarine canyons only one, suggested by Daly in 1936 and subsequently developed, appears to be reasonably satisfactory. It may be briefly summarized as follows. During the glacial epochs the continental shelf was everywhere exposed down to about 300 feet below present sea level. Waves and currents, then specially strong because of the stormy weather of glacial times, churned up the muds of the outer part of the shelf and gave rise to an undertow and bottom layer of unusually turbid water. The mud-laden water, being heavier than the clear water above it, began to flow down the shelf as a *suspension current* with a velocity determined by the density of the suspension and the angle of slope. By guiding and concentrating the flow of the loaded water chance depressions would thus become selectively eroded into furrows which thereafter would canalize and accentuate the currents. On reaching the continental slope (with a gradient of about 1 in 15, a hundred times steeper than that of the average shelf) the currents would gather speed and thus gain additional erosive

[*H. S. Bell, U.S. Dept. of Agriculture*

Fig. 169

A suspension current of muddy water flowing down a submerged " delta " of sand in a laboratory tank

power. Once started, such submarine streams would be self-perpetuating, and even self-accelerating, since erosion would add to the muddiness of the water, and therefore to its effective density. The inference is inevitable that on the continental slopes erosion should have been altogether more vigorous than on the shelf where the currents were engendered. Subsidiary processes which would co-operate with suspension currents in the development of the canyons include undercutting of the floors and sides by emerging springs, and slumping of loose, water-saturated sediment. Earthquakes might well act as a trigger to set submarine " landslips " moving. Each of these processes has been regarded as of major importance by certain geologists, but it is difficult to see how either or both (without the guiding hand of suspension currents) could be responsible for a submarine topography that bears all the hall-marks of erosion by running water.

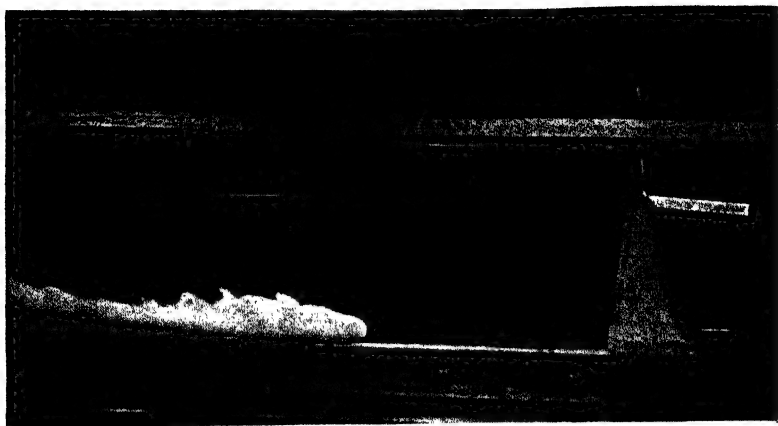
There can be no doubt about the reality and efficacy of the main process envisaged by Daly. Where the Rhône, milky with glacial sediment, flows into Lake Geneva, its waters visibly dive under the clear lake water and flow through a five-mile trench towards the deepest part of the lake. Moreover, carefully designed series of tank experiments carried out by

[H. S. Bell, U.S. Dept. of Agriculture

FIG. 170

A suspension current of muddy water approaching the dam in a laboratory tank

Kuenen in Holland, and independently by Bell in the United States, have demonstrated that suspension currents do, in fact, behave as described by Daly (Figs. 169 and 170). The only doubt still remaining is whether these currents could erode resistant rocks, such as have been collected by dredging from the walls of some of the canyons, or whether this feature requires some additional explanation.

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Chapter XV

LIFE AS A ROCK BUILDER

Life as a Geological Agent

In earlier chapters certain aspects of the geological work accomplished by living organisms have already been touched on : the breaking up of the sub-soil by roots ; the growth of soils ; the protection of soils by forests and prairie grasses ; the fixation of sand dunes ; and the comminution of materials by worms and other burrowing animals. Apart from man, who at the present day is contributing to erosion and transport on a gigantic scale, organisms are of limited importance as rock breakers, but in virtue of their biochemical activities they contribute on a very considerable scale to the chemical weathering of rocks.

In particular it is worth noticing that practically all the oxygen now present in the atmosphere and all the oxygen that has been used up in weathering processes has been liberated from carbon dioxide by green plants during their growth (p. 330). The only other known source of free oxygen is due to the action of certain bacteria which liberate oxygen from nitrates, which they turn into ammonia, or from sulphates, which they reduce to sulphides (such as pyrite) or even to sulphur itself. Since oxygen has accumulated throughout geological time as a by-product of plant life, despite the enormous amount used up in oxidation (including breathing), it follows that there must be an equivalent amount of carbon elsewhere. Part of this is present in the living tissues of the plants and animals of the present day. Both on land and in the sea certain animals eat plants and other animals devour the plant-eaters. Thus a great deal of organic matter is simply transferred from one organism to another. Of the balance, part decays, largely as a result of bacterial attack, and passes away as carbon dioxide and water ; while

the remainder, in various states of preservation according to the stage of decomposition reached before and after burial, is found in soils and swamps, in carbonaceous and bituminous shales, and in more concentrated deposits of peat, coal, and petroleum. Natural fuels and the oxygen required for their combustion are two of the most important end products of vital activities (see Fig. 177). This aspect of the work of life forms the subject of the following chapter.

Besides the accumulations of organic matter mentioned above, there are immensely greater deposits which are largely composed of the shells or other protective and supporting structures of once-living organisms. Most of these hard parts consist essentially of calcium carbonate secreted from sea water by animals such as molluscs (commonly known as shell-fish), sea urchins, corals, and the tiny single-celled foraminifera (Plate 72A and B), and by plants of which algae (a group including seaweeds) are the chief. After death, the hard parts persist and accumulate as shell deposits (Plate 9B), coral reefs, deep-sea oozes, and the like; all raw materials of limestones in the making. Other single-celled animals and plants, known respectively as radiolarians (Plate 72C) and diatoms, extract silica, and encase themselves within microscopic shells of opal. The resulting siliceous deposits constitute two important varieties of the deep-sea oozes. Other organisms, such as fresh-water mussels and snails, and green algae, contribute calcareous materials to deposits forming in fresh-water lakes, lagoons, and estuaries; and fresh-water diatoms, which abound in the lakes of glaciated districts, similarly provide siliceous deposits known as *diatomaceous earth*. But the marine examples are of enormously greater abundance.

Bacteria also help to form limestones by what may be called biochemical precipitation. It was mentioned above that certain bacteria turn nitrogen compounds into ammonia. The latter has the effect of precipitating calcium carbonate from sea water, and on the shallow banks between Cuba and the Bahamas considerable deposits are now being formed in this way. Bacteria are also concerned in the precipitation of

limonite from the waters of lakes and marshes, notably in Sweden and Finland, where bog iron ore of this kind has been extracted on a commercial scale.

Phosphates are of great value because of their vital importance as fertilizers, and because workable deposits are far less common than we could wish. Most of them have resulted directly or indirectly from organic activities. Calcium phosphate is particularly concentrated in the bones, teeth, and excrement of vertebrates, especially fishes. Vast numbers of fish are sometimes killed by the shock of earthquake vibrations passing through sea water, and their remains then accumulate as *bone beds*. Another source is provided by the droppings of countless generations of fish-eating birds on coasts and oceanic islands, which thus become thickly encrusted with *guano*.

Marine Deposits

According to their location on the sea floor (Fig. 171), marine deposits are classified as follows. *Littoral* deposits are those formed between high and low tides. *Shallow water* deposits are those which collect on the continental shelf and

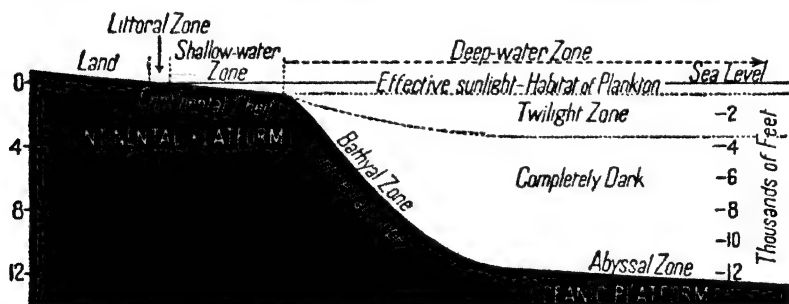



Fig. 171

Schematic section to show the zones of marine sedimentation

at similar depths elsewhere, that is, between low tide and 100 fathoms. Below this level are the muds and oozes referred to as *deep sea* or *deep water* deposits. The muds, etc., of the continental slope, and of similar depths around oceanic islands,

belong to the *bathyal* zone ; while the oozes of the deep ocean floor belong to the *abyssal* zone.

According to the source of the materials, marine deposits fall into two main groups : *terrigenous*—derived from the land by river transport and coast erosion ; and *organic*—comprising the calcareous and siliceous shells and other remains of marine organisms. The terrigenous deposits are naturally found in greatest bulk bordering the lands. Sediment that is swept over the edge of the continental shelf comes to rest on the slopes beyond. The abyssal ocean floor receives supplies of land detritus only from wind-borne dust and rare icebergs. These sources of supply are so scanty that the rate of accumulation is extremely slow.

The marine organisms that contribute most conspicuously to the sediments of the littoral and shallow water zones belong to a group known collectively as the *Benthos* (bottom dwellers). This includes seaweeds, molluscs, sea urchins and corals, and other forms that live on the sea floor. Many of them are firmly attached to the bottom. Deposits of shells or of their wave-concentrated fragments are formed in great abundance in favourable situations, while elsewhere similar remains are dispersed as fossils through the terrigenous deposits. The North Sea is mainly floored with terrigenous material, but off the Kentish coast and between the Thames and the Hook of Holland there are patches of several square miles consisting almost entirely of large shells. The shelly sands of some of the Cornish beaches have already been mentioned (p. 293). These are but relatively small examples of shelly limestones in the making. Far more extensive accumulations occur off limestone coasts and in other situations where the organic remains are not smothered by sand and mud. The reefs and atolls built up by corals and their associates in the shallow water of warm, uncontaminated seas illustrate limestone-building on so spectacular a scale that they are reserved for a more detailed description.

Organic deposits of the above types which have accumulated off continental shores or on the flanks of oceanic islands are described as *neritic* (Gr. *neritos*, a mussel). The organic

oozes and red clay of the abyssal zone are distinguished as *pelagic* deposits (Gr. *pelagos*, the sea). The oozes are largely composed of the remains of marine organisms belonging to a group called the *Plankton* (the wanderers). This includes the single-celled marine plants (diatoms) and animals (foraminifera and radiolarians) ; certain floating molluscs known as " sea butterflies " or pteropods ; most of the eggs and larvæ of the benthos and other marine organisms ; and all other forms which, unlike fishes, have no means of self-locomotion. The pteropods are blown along the surface by the wind, but the others, nearly all microscopically small, are passively suspended in the water. Diatoms, being plants, cannot live below the depth of effective sunlight penetration, which in the open ocean reaches a maximum of about 650 feet. Though individually quite invisible to the unaided eye, the diatoms are present in such prodigious numbers that they turn the sea in which they live into a kind of thin vegetable soup. This forms the main food supply of the rest of the plankton, whose habitat is therefore similarly confined to the sunlit zone.

From this prolific overhead source the sea floor receives a slow but steady rain of plankton shells which have escaped destruction by being eaten or by being dissolved in the sea water as they sank. In the shallow-water zone the tiny shells are generally lost in an overwhelming abundance of terrigenous and neritic materials. In the bathyal zone, where the rate of supply of terrigenous sediment is less overpowering, they make a bigger show and can be readily found in the blue and green muds, both of which are characteristically calcareous deposits. In the abyssal zone, however, the plankton shells accumulate with little contamination from other sources, to form the deep-sea oozes which, together with the red clay, constitute the pelagic deposits.

Fishes, whales, and other marine animals which go actively after their food supply are grouped as the *Nekton* (swimmers). These contribute to all the marine deposits on a limited scale, but concentrated remains, such as the bone beds already mentioned as sources of phosphates, are quite rare.

The adjoining table summarizes the leading types of deposits

now forming on the sea floor, classified according to the zones of deposition and the sources of material as reviewed in the preceding paragraphs. A systematic description of all these deposits would require more space than is available, but coral reefs and the chief varieties of the pelagic deposits will serve as illustrative examples of special interest.

MODERN MARINE DEPOSITS

Kinds of Material / *Zones of Depsition*	Terrigenous Deposits	Chemical and Biochemical Precipitates	Organic Deposits	
			Neritic (Mainly *Benthos*)	Pelagic (Mainly *Plankton*)
Littoral Zone Shallow Water Zone	Shingle Gravel Sands Muds	Oolite sands Calcareous muds Cementing materials	Shell gravels and Shell sands Coral reefs and Coral sands	
	<————	——(10%)—	————>	
Deep-Water Zone	Deep Sea Muds *of the Bathyal zone* Green, black and blue muds Volcanic muds (With varying amounts of plankton remains) (15%)	Cementing materials	Coral muds	Deep-Sea Oozes *of the Abyssal zone* Pteropod ooze Globigerina ooze Diatom ooze Radiolarian ooze (41%)
				Insoluble Residues *from various sources* Red Clay (34%)

The figures in brackets represent the approximate areas covered by the various groups of deposits, expressed as percentages of the area of the ocean floor

Pelagic Deposits

The composition and distribution of the deep-sea oozes depend on the temperature of the surface waters and the depth of the underlying ocean floor. Diatoms, for example, flourish

particularly well in cold circumpolar seas which are unfavourable to a profusion of other forms. Radiolarians, on the other hand, are especially abundant in warm tropical waters. Foraminifera, of which *Globigerina* is the commonest genus, abound in tropical and temperate regions and the distribution of globigerina ooze is therefore less restricted. The tiny calcareous and opaline shells, being extremely delicate and often of intricate design, readily lend themselves to attack by solution as they sink towards the bottom. The solvent power of sea-water increases with depth : directly because of the increasing pressure and indirectly because the proportion of gases in solution, mainly carbon dioxide, also becomes higher as the pressure rises and the temperature falls. The globigerina and other calcareous foraminifera dissolve more rapidly than the radiolarians and other siliceous forms. Only a few of the larger varieties succeed in reaching depths of 3,000 fathoms, and in the next 500 fathoms even these are lost. As a well individualised deposit *globigerina ooze* is most characteristically developed at medium depths on the ocean floor, that is, round about 2,000 fathoms. The siliceous remains persist to greater depths, some of them down to 5,000 fathoms, the average for *radiolarian ooze* being about 3,000.

Over 50 million square miles of the ocean floor lies beyond the reach of more than traces of the plankton remains. Here accumulate the materials that form the basis of the *Red Clay* : (*a*) volcanic products from wind-borne dust, submarine eruptions, and fragments of pumice that have floated far from their source before sinking ; (*b*) non-volcanic wind-borne dust ; (*c*) insoluble organic relics like shark's teeth and the ear-bones of whales ; (*d*) the dust of meteorites and occasional larger fragments which have fallen into the sea from the sky ; and locally, (*e*) debris dropped from far-travelled icebergs. Meteorite dust falls everywhere, of course, but it is only in the red clay that it is not smothered beyond recognition. The red clay accumulates so slowly that some of the shark's teeth lying unburied on the surface are those of species now extinct. Many of the ingredients listed above have decomposed into clay, heavily stained by ferruginous matter which gives the

deposit a brick-red or chocolate-brown colour. Other secondary products found in the red clay include black nodules of manganese oxide and crystals of various silicate and other minerals. Where the depth is not excessive undissolved plankton remains appear, and as the proportion of these increases with decreasing depth the red clay ingredients become more and more diluted until the deposits pass into radiolarian ooze in some localities or into globigerina ooze in others.

In the following table the average composition of each of the chief pelagic deposits is given :

Constituents	Globigerina Ooze	Red Clay	Radiolarian Ooze	Diatom Ooze
Calcareous remains	64	6	4	23
Siliceous remains	2	2	54	41
Mineral matter .	34	92	42	36
Area in millions of square miles . .	49·5	51·5	2·3	11

Radiolarian Ooze (Plate 72c) is essentially a variety of red clay that is notably rich in the remains of radiolarians. Diatoms and sponge spicules are also commonly present. It occurs beneath the tropical belts of the Pacific and Indian oceans, where the warm surface waters favour an unusual profusion of radiolarians, and where the great depth prevents more than a scanty supply of calcareous remains.

Although they occur everywhere, diatoms are most abundant relative to the rest of the plankton around Antarctica and in the extreme north of the Pacific. The delicately ornamented shells accumulate there, as *Diatom Ooze*, together with certain species of foraminifera that can live in cold water. Contamination by terrigenous material, much of which is derived from floating ice, is commonly abundant.

Globigerina Ooze is by far the most widespread variety and is especially characteristic of the Atlantic floor. It contains

foraminifera in great abundance and variety (Plate 72A), among which the shells of *Globigerina*, each consisting of several globular chambers, are the commonest (Plate 72B). The proportion of calcium carbonate varies with the depth, ranging from 97 per cent. in samples from 400 fathoms to 30 per cent. in those from 2,600 fathoms, the balance being made up of other plankton remains, and ingredients like those of the red clay, into which the globigerina ooze merges at its lower margins. In the shallower depths, over sub-tropical and tropical submarine banks and ridges, the shells of pteropods locally become abundant, and when they predominate the deposit is distinguished as *Pteropod ooze*. Another important variety is characterised by the button-shaped remains (coccoliths) of certain lime-secreting algae which flourish in sub-tropical waters.

Geological Interest of the Pelagic Deposits

A century ago nothing was known of the deep-sea deposits. Globigerina ooze, dredged up by one of the cable-laying steamers in 1852, was the first to be discovered. A systematic exploration of the ocean floor was carried out by the famous *Challenger* Expedition of the years 1872–76. The thousands of samples then brought up are described in one of the fifty bulky volumes in which the scientific results of that great enterprise are recorded. Since then certain parts of the ocean floor have been investigated in greater detail, but only in recent years has any really fundamental advance been made.

In 1934 Piggot successfully developed a sounding apparatus for securing core samples of abyssal deposits. The apparatus consists of a long metal tube which, on arriving at the bottom, is automatically forced into the sediment by an explosion of cannon powder contained in a kind of gun attached to its upper end. During 1936 cores up to ten feet long were obtained along a traverse across the North Atlantic from Newfoundland to Ireland ; seven of these came from depths exceeding 2,000 fathoms. So slowly has the geological record

accumulated in these quiet depths that the cores represent at least a million years of oceanic deposition. Examination of the sequence shows that the four glacial epochs are all clearly represented. The foraminifera of the glacial bands are, moreover, found to be of types that live in cold waters, whereas those of the interglacial bands indicate that the surface waters were then as warm as, or even warmer than, those of to-day.

A fact of great significance is that no representatives of the abyssal deposits of former ages have been found among the formations now exposed on the continent, except in certain marginal islands. The Chalk might appear to be an exception, for it is a limestone that in some respects resembles a highly calcareous globigerina ooze. But the Chalk foraminifera are largely shallow-water forms, and with them are associated many larger fossils of the benthos group. These all have characteristically thick shells, such as are grown only by organisms that have to withstand the turmoil of vigorous waves. Thus the Chalk is not an abyssal deposit. The lands surrounding the Chalk sea were so low-lying that they provided little or no terrigenous material to the sea floor outside the littoral zone, and in consequence a thick uncontaminated limestone, characterised by an unusual abundance of foraminifera, was able to accumulate in the thirty million years or so during which these exceptional conditions lasted.

In the Dutch East Indies Jurassic and Cretaceous formations have been discovered which contain alternating layers of indurated red clay and radiolarian ooze, associated with shallow-water and bathyal sediments. Similar uplifted deposits, accompanied by globigerina ooze, occur in Barbados in the West Indies. Here they lie on Tertiary continental sediments, including coal seams, thus presenting "clear evidence that portions of a continental area might be depressed to oceanic depths and re-elevated." Evidence of this kind, however, is confined to a few tracts along the folded margins of the continents. There is nowhere any indication that the oceanic platform itself has become part of a continental region.

Coral Reefs and Atolls

In favourable situations in tropical seas corals, together with all the organisms to which they give shelter and attachment, grow in such profusion that they build up reefs and

Fig. 172

Coral reefs. Fringing and barrier reefs of Mayotta, Comoro Is., north end of Mozambique Channel. The outlines of the islands suggest recent submergence

islands of very considerable size. Clothed in vivid green, crowned by the coconut palm, and fringed with the white foam of the ceaseless surf, the " low islands " of the Elizabethan

mariners have a reputation for dazzling but treacherous beauty. Dangerous to navigation and difficult to explore, they have been equally tantalising to geologists who sought to account for their existence. Darwin was the first to face the problems in a scientific spirit and by him coral reefs were divided into three main classes (Figs. 172–174) :

(*a*) *Fringing reefs*, consisting of a veneer or platform of coral which at low tide is seen to be in continuity with the shore. The width is often half a mile or more, and the seaward side slopes steeply down to the normal sea floor.

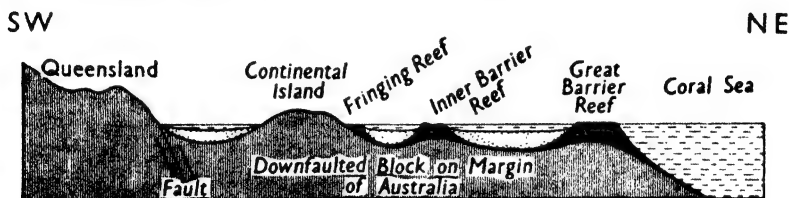



FIG. 173

Section to illustrate the relationship of the Great Barrier Reef to the coast of Queensland (*After J. A. Steers*)
Reef rock, black ; lagoon and channel sediments, dotted

(*b*) *Barrier reefs*, situated up to several miles off-shore, with an intervening lagoon. The thousand-mile complex of reefs known as the Great Barrier Reef, which forms a gigantic natural breakwater off the north-east coast of Australia, is by far the greatest coral structure in the world (Plate 73A and Fig. 173). Most barrier reefs, however, of which there are countless examples, are island-encircling structures forming irregular rings of variable width, more or less interrupted by open passages on the leeward side (Fig. 172).

(*c*) *Atolls*, resembling barrier reefs, but without the central island (Plate 73B and Fig. 174). They are essentially low-lying ring-shaped islands enclosing a lagoon which again is generally connected with the open sea by passages on the leeward side.

Reef-building coral live in colonies of thousands of tiny individuals (polyps), each occupying a cup-shaped depression

FIG. 174
Map of the Suva Diva atoll, Indian Ocean (50 × 40 miles), showing the depths of the lagoon floor in fathoms (*After R. A. Daly*)

in a calcareous framework which is common to the whole colony. As the successive generations of corals grow outwards through the restless waters in their competition for food, the stony framework also branches upwards and outwards and grows into forms that resemble plants, some being like shrubs and others like cushioned rock-plants. The interspaces between the dead coralline structures are cemented and bound together by calcareous algae called nullipores. These precipitate calcium carbonate within themselves, and still more as incrustations which coat their surfaces and cover the coral growths to which they are attached. Other contributions are made by shelled molluscs, foraminifera, calcareous worms, and

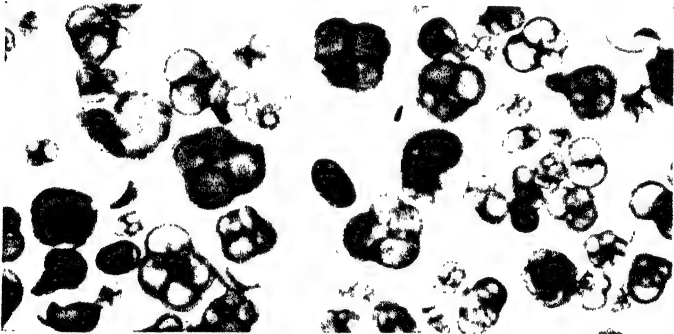
bacteria, and the whole assemblage accumulates to form a white porous limestone which gradually becomes more coherent as it is buried and subjected to prolonged saturation by sea water.

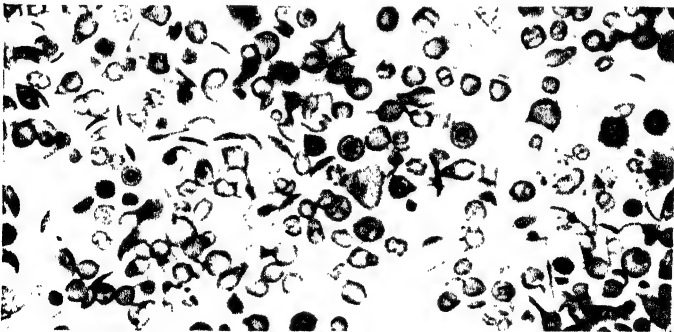
The development and maintenance of coral reefs depend upon the conditions that favour a vigorous growth of the living colonies. A thriving reef has to contend not only with the waves, but also with boring organisms and voracious crustaceans that feed on the bodies of the individual corals. The reef represents the margin of success in a never-ceasing struggle against death and extinction. Not only have the corals and nullipores to supply material to maintain a flourishing living face, they have also to provide the broken masses of coral rock and other debris that accumulate to form the visible reef and its seaward foundations. On the lagoon or landward side of the living face there is the *reef flat*, consisting of material thrown up by the breakers to a height of 10–15 feet. A certain amount of debris is also washed over into the lagoon by heavy seas that sweep the reef. On the seaward side of the growing face the reef passes into a talus slope that may descend to very great depths on the flanks of oceanic barrier reefs and atolls.

Corals require a mean temperature of not less than 68° F., and reefs and atolls are therefore restricted to a zone lying between latitudes 30° N. and S., except locally where warm currents carry higher temperatures to the north or south of these limits. The reefs of the Bermudas, for example, are dependent upon the warmth of the Gulf Stream. Along the torrid belts of the oceans the equatorial currents drift towards the west, becoming warmer on the way, and consequently reefs flourish far more successfully in the western parts of the oceans than on their colder eastern shores.

The water must be clear and salt. Opposite the mouths of rivers, where the diluted sea-water carries suspended silt and mud, corals cannot live and no reefs appear. Conversely, reefs grow best on the seaward edge of the reef, where splashing waves, rising tides, and warm currents bring them constantly renewed supplies of oxygen and food. Corals cannot long survive exposure above the water, and consequently living reefs

G. O'Neill

(A) Foraminifera from Globigerina Ooze, South Atlantic. × 30

R. M. Craig

(B) Globigerina from Ooze, Porcupine Bank, west of Ireland. × 25

[R. M. Craig

(C) Radiolaria from Ooze, South Pacific. × 25

[Am. Mus. Nat. History, N.Y.

(A) Coral growths exposed on the Great Barrier Reef at low tide, Port Denison, Australia

[J. P. Capin, Am. Mus. Nat. History, N.Y.

(B) Hao Atoll, Tuamotos Islands, Pacific Ocean

can never grow much above low-tide level. Dead reefs are found above sea level, but they have been uplifted into such positions by earth movements, to which they are therefore a most reliable index. On the other hand, reef-building corals require sunlight and do not grow freely at depths greater than about 25 fathoms ; nullipores are similarly restricted to about 50 fathoms. A necessity for reef formation is therefore the pre-existence of a platform not far below sea level. Reefs and atolls may be " drowned " by rapid subsidence, and several examples of reefs and atolls that have been killed off in this way have been discovered on the sea floor. It follows from the above considerations that the living corals and the growing face of the reef tend to spread upwards and outwards towards the surface waters of the open sea.

The Origin of Barrier Reefs and Atolls

The origin of fringing reefs is easy to understand. Minute coral larvae drift with the ocean currents, and those that reach suitable shores find attachment and start new reefs that gradually develop seawards. Barrier reefs and atolls, however, are remarkable in that they generally rise from depths where no corals or nullipores could live. There are two possibilities : either the reefs have grown upwards from submerged banks not more than, say, 50 fathoms below the surface, or they have grown upwards and outwards from fringing reefs during the submergence of the land or island to which they were originally attached. Another feature that calls for explanation is that the lagoons have nearly flat floors and depths that are all of the same order, the range being from about 45 fathoms for the larger examples, which may be several miles across, to 25 fathoms for the smaller ones.

The first general explanation was offered by Darwin as a result of the observations he made during his celebrated voyage in the *Beagle*. He visualized all reefs and atolls as different stages in a single process (Fig. 175). Growth begins with the building of a fringing reef around, let us say, a volcanic island.

Subsidence of the island combined with continuous growth converts the reef into a barrier reef. Since corals can grow upwards at a rate of about a foot in ten years it will rarely happen that they are unable to keep pace with the movement. The submerged area between the island and the rim of coral rock forms the lagoon. By further subsidence the summit of the central island sinks out of sight, and the barrier reef becomes an atoll.

Darwin's simple theory has not passed unchallenged, but it satisfactorily accounts for most of the features associated with reefs. The reality of subsidence—or at least of a change of sea level—is proved by the drowned valleys and embayed

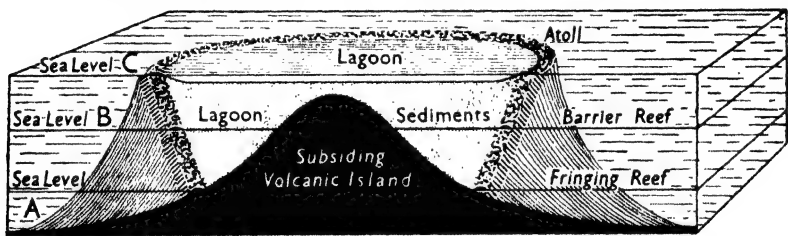



Fig. 175

Diagram to illustrate Darwin's theory of the successive development of fringing reef, barrier reef, and atoll around a subsiding island

shore lines of the land inside the lagoons of barrier reefs. The Great Barrier Reef has grown on the edge of a down-faulted area, which was formerly the coastal plain of Queensland and part of New South Wales. Uplifted atolls in Timor and elsewhere are found to lie unconformably on an eroded foundation, exactly as the theory requires. The theory does not, however, make it clear how the lagoons of the present day have come to be so remarkably uniform in depth. Fig. 175 shows the enormous quantity of lagoon sediment necessary to fill in the " moat " around a subsiding volcanic island. Alternatively, the flat lagoon floors of atolls and island-encircling barrier reefs suggest that the corals grew upwards from the edges of submerged platforms worn down by marine erosion.

In 1910 Daly showed that these features are an inevitable result of recent and Pleistocene changes of climate and sea

level. He had already noticed the narrowness—and therefore the youthfulness—of the reefs fringing the Hawaiian Islands. Connecting this youthfulness with the discovery that a former glacier had left its traces on the flanks of Mauna Kea, he came to the conclusion that corals could not have flourished along those shores during the glacial epochs and that the existing reefs must have grown there during post-glacial time. During the glacial epochs the fall of temperature must have killed off most of the pre-existing reef-builders, leaving only a few sheltered spots from which the active reefs of the interglacial stages, and finally those of the present day, could be colonised. Moreover, during the height of each glaciation the level of the oceans must have been about 300 feet or 50 fathoms lower than to-day. As a result of the lowered sea level, pre-glacial islands and reefs would be steadily attacked by the waves, and in many places reduced to platforms of marine erosion near, or a few fathoms below, the sea level of the time.

Thus, innumerable platforms—many of them being the truncated summits of oceanic volcanoes—were formed at about the right depth to account for the existing floors (Fig. 176). The latest colonisation of the platforms and the upbuilding of the encircling reefs by corals present no difficulty. It is about 25,000 years since the melting of the ice locked up in the continental ice-sheets of Europe and North America began to restore to the oceans the water previously abstracted. With a growth rate of a foot or so in ten years the corals could readily keep pace not only with the rising sea level, but also with the necessity to provide material for the wave-built reef-flats and for the talus slopes on the seaward flanks.

The lagoons must, of course, have been somewhat shallowed by deposition. The smaller the lagoon the more rapidly its floor would be built up by sedimentation, because of the proportionately greater length of reef across which debris could be washed. This consideration is matched by the observed fact that the lagoon depths increase as the widths increase. Submerged platforms in the colder oceanic regions where corals failed to gain a footing have received very little sediment and their depths are correspondingly greater.

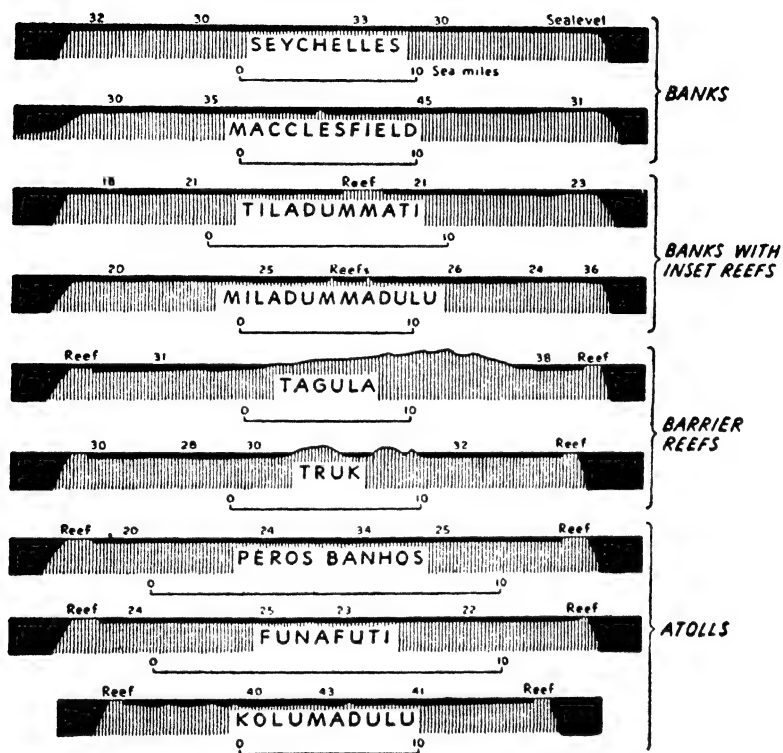



FIG. 176

Sections demonstrating the flatness of the floors of reef lagoons and the close similarity of their depths to those of submerged banks
(*From R. A. Daly, "The Floor of the Ocean," by permission*)

Darwin's subsidence theory leaves the origin of the platforms unexplained. Daly's "Glacial-Control" theory provides an adequate explanation. In all regions the rise of sea level since the withdrawal of the ice sheets has been a definite factor in the development of coral reefs and atolls. But wherever earth movements have been in operation they too have been a factor that cannot be ignored. Their importance is clearly indicated by the occurrence of both "drowned" and elevated reefs in regions such as the outer margin of the Dutch East Indies, where orogenic movements are now or have

recently been in progress. In Timor uplifted atolls furnish evidence that subsidence and coral growth were succeeded by upheaval and coral extinction. Moreover, it seems probable that many volcanic islands may have subsided in consequence either of isostatic readjustment, or of contraction of the underlying foundations.

Darwin's theory refers to submergence by earth movements, while Daly's refers to submergence by a rising sea level. Neither by itself provides an all-embracing explanation of coral reefs, but together, as a complementary pair, they solve all the major problems.

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CHAPTER XVI

LIFE AS A FUEL MAKER: COAL AND OIL

THE SOURCES OF NATURAL FUELS

CARBON dioxide is the primary source of the carbon compounds of all living organisms and of all those that have lived in past ages. Under the influence of the sun's rays green plants, including most of the bacteria, synthesize carbon dioxide and water into carbohydrates, such as cellulose and starch, both $(C_6H_{10}O_5)_x$, and sugar $(C_{12}H_{22}O_{11})$. Since these compounds

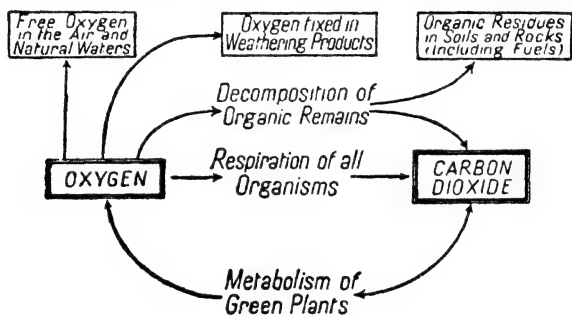



FIG. 177

Diagram to illustrate the Carbon Dioxide–Oxygen Cycle and its by-products

are equivalent to carbon and water, their formation involves liberation of the oxygen which was originally combined with the carbon. Some of the oxygen so set free recombines with the carbon of organic matter, both living and dead; another part is used up in weathering processes; and the balance passes into the atmosphere or into the sea. The cycle of changes is schematically summarized in Fig. 177.

If all the decaying remains of dead organisms were completely oxidized there would be no free oxygen left over. Under water-logged conditions, however, oxidation is not complete. The decomposition products of vegetation, for example, accumulate as humus in the soil and as deposits of

peat in bogs and swamps. The buried peat deposits of former ages have been transformed into coal seams. In marine sediments a high proportion of the organic material of plant and animal life is either eaten or lost by oxidation, but some escapes complete destruction and is entrapped in muddy deposits to form the minute droplets of oil and bubbles of gas which are the source materials of the concentrated " pools " of petroleum and natural gas found in oilfields. Life is thus responsible for all the natural fuels, including wood, peat, coal, oil, and gas, and for the enormously greater amount of carbonaceous and bituminous matter that is dispersed through shales and other sedimentary rocks.

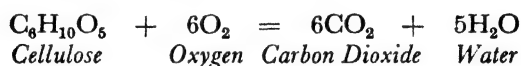
It is of interest to attempt an approximate balance-sheet between the carbon of organic matter and the oxygen complementary to it. The following table gives some idea of the prodigious amounts involved, and bears eloquent witness to the work of countless generations of countless millions of plants and animals.

Carbon in	*Millions of tons*	Oxygen	*Millions of tons*
Living matter	700,000	In the air	1,223,500,000
Soil	400,000		
Peat	1,200,000	Added to weathering products and now in sediments	8,000,000,000*
Lignite and Brown Coal	2,100,000		
Bituminous Coal	3,200,000		
Anthracite	600,000		
Ordinary Sediments	4,576,000,000*	Dissolved in the ocean	12,000,000
Total	4,584,200,000	Total	9,235,500,000

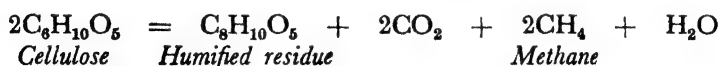
The figures marked with an asterisk are only rough estimates, as it is impossible to assess with accuracy either the total mass of all sedimentary rocks or their average composition. Nevertheless, the totals for carbon and oxygen turn out to be of the same order, with oxygen in excess, as it should be if both have been derived from carbon dioxide. No figure is given above for the carbon in oil and natural gas, as any reasonable guess as to ultimate resources would be quite negligible in comparison with the figures for the other repositories of carbon. So far 13,000 million tons of oil have been discovered, and half of this total has already been extracted from oilfields and used.

Peat

The development of vegetable mould and humus from decaying plant remains has already been mentioned in connection with the soil (p. 122). Dead plant debris is at once attacked by bacteria and fungi, and in the presence of sunlight and oxygen the cellulose which is the basic substance of nearly all plant tissues rapidly disappears, the ultimate products being carbon dioxide and water :

$$\underset{\textit{Cellulose}}{C_6H_{10}O_5} + \underset{\textit{Oxygen}}{6O_2} = \underset{\textit{Carbon Dioxide}}{6CO_2} + \underset{\textit{Water}}{5H_2O}$$

But in water-logged environments, such as bogs and swamps, the degree of putrefaction is limited by the paucity or absence of oxygen and the generation of antiseptic organic acids which inhibit the bacterial activities. Under these conditions the softer and finely macerated plant debris changes into a dark brown jelly-like humus. Part of this soaks into the cells of fragments of wood, bark, roots, twigs, etc., which are also being " humified," and the cellular structures of these remains are in consequence often wonderfully well preserved. All the humified products, together with a variable proportion of the less destructible materials, such as resin and the waxy pollen cases and spores, accumulate to form deposits of peat.

The process of humification enriches the residue in carbon, as indicated by the following equation, which approximately represents the chemical changes involved :

$$\underset{\textit{Cellulose}}{2C_6H_{10}O_5} = \underset{\textit{Humified residue}}{C_8H_{10}O_5} + 2CO_2 + \underset{\textit{Methane}}{2CH_4} + H_2O$$

Methane, more familiarly known as marsh gas, is highly inflammable, and its pale flames are responsible for the " will-o'-the-wisp " which is occasionally seen flickering over the surface of a bog. In coal mines, where the gas sometimes escapes in disastrous quantities from the coal face, it is the chief constituent of the dreaded fire damp.

The vegetation which contributes to peat formation ranges

from mosses (bog peat) to trees (forest peat—Plate 74A), and the environment may be a swampy lowland or a water-logged upland with imperfect drainage. The climate must therefore be humid and the conditions such that growth exceeds wastage. In the bogs of cool humid regions the rate of decay lags behind because of the low temperature, whereas in the densely forested swamps of tropical regions the phenomenal rapidity of growth more than keeps pace with the high rate of decay.

A special variety of peat accumulates at the bottom of lakes and pools surrounded by marsh vegetation. Wind-blown pollen and leaves fall into the water, and all manner of organic particles drift into it. Eventually these settle down to form a layer of organic ooze. Fresh-water algae may add further contributions. Locally the spores and algal remains may predominate, giving rise to a deposit that is specially rich in the waxy and oily ingredients of vegetation. If streams are flowing into the water the ooze is likely to be contaminated by a certain amount of muddy sediment.

Many thousands of the shallow lakes that formerly occupied depressions in areas strewn with glacial deposits have been converted into peat bogs by the steady encroachment of marsh and swamp vegetation, and in others the process of infilling is still in progress. The rushes, reeds, and pond weeds gradually advance over the dark gelatinous slime formed from the residues of earlier generations. Floating vegetation sometimes grows out in thick spongy rafts across the surface. Meanwhile the floor is being built up as organic ooze accumulates, and finally the site of the lake becomes a swamp. The treacherous surface may be covered with quaking tussocks of sphagnum moss, as in the bogs of Ireland. Where the drainage conditions are suitable, the plant sequence may culminate in a forest of trees with roots adapted to the precarious foundation through which they spread.

On a more extensive scale swamps are developed from the shallow lagoons and lakes of low-lying coastal plains, flood plains, and deltas. The Dismal Swamp of the coastal plain of Virginia and North Carolina is an immense forested area, only

a few feet above sea level, interspersed with stretches of open water (Fig. 167). Here 1,500 square miles have been covered with peat averaging 7 feet in thickness. Along the north-east coast of Sumatra there are many scattered swamps supporting almost impenetrable tropical jungles. In one of these peat is known to have accumulated to a depth of 30 feet.

The densely forested swamps of the Ganges and other tropical deltas (Plate 75B) provide ideal conditions for peat growth and serve to illustrate the climatic and geographical conditions under which the coal seams of the Carboniferous period originated. Moreover, borings through the Ganges delta reveal a succession of buried peat beds with intervening deposits of sand and clay. The sequence points to repeated alternations of subsidence and standstill, with the actual surface never far from sea level.

As peat accumulates year after year the entangled water is squeezed out of the lower layers and the peat shrinks and consolidates. It still contains a high proportion of water, however, and before being used as a fuel prolonged air-drying is necessary. In appearance it then ranges from a light brown fibrous or woody material to a dark brown or black amorphous substance.

Coal and its Varieties

Peat becomes still further compacted when it is buried beneath a cover of clays and sands. As the overhead pressure increases water and gases continue to be driven off, their composition being such that the residue is progressively enriched in carbon until it is transformed into a variety of coal (Fig. 178). It has been estimated that at least a foot of peat is necessary to make an inch of ordinary coal. The essential conditions for the development of a coal seam are thus (*a*) long-continued growth of peat; and (*b*) subsidence of the area and burial of the peat beneath a thick accumulation of sediments.

Considerable variation in the character of coal is naturally to be expected according to (*a*) the nature of the plant residues

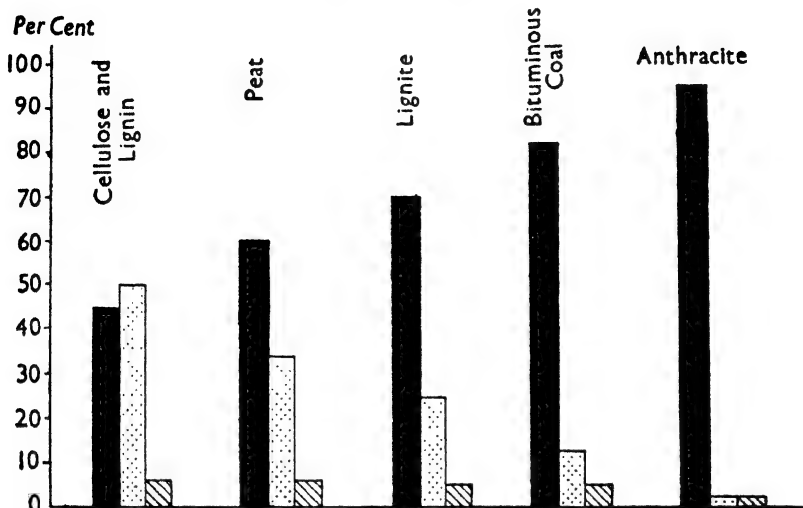



FIG. 178

Diagram to illustrate the variation in composition from woody material through peat to coal and anthracite. Black columns represent carbon ; dotted columns, oxygen ; and line-shaded columns, hydrogen. (*After H. G. A. Hickling*)

—which determines the *type* of coal material ; and (*b*) the stage of chemical alteration which has been reached—which determines the *rank* of the coal.

In normal coals the remains of wood and bark predominate, indicating derivation from forest peats. Coal of the lowest rank, that is, the variety most like peat, is called *lignite.* It commonly retains visible vegetable structures, but there are also varieties, often known as *brown coal,* in which the woody tissues are obscure. Lignites and brown coals are common in the Cretaceous and Tertiary coalfields of Europe and North America, but are of no importance in Britain.

The familiar shining black or dark grey coals of the British and other Carboniferous coalfields belong to a group of fuels of higher rank known collectively as *bituminous coal.* This term does not imply the presence of the material properly called bitumen, but has reference to the fact that in the manufacture of coal gas and coke one of the distillation products, *coal tar,* is of a bituminous nature. Coal of the highest rank—called

anthracite—occurs in certain localities (*e.g.* in South Wales) where unusually high pressure due to deep burial and subsequent earth movements, combined with a moderate increase of temperature, has facilitated the driving-off of nearly all the volatile constituents. Anthracite is hard, brittle, and stony-looking ; does not soil the fingers ; burns with a smokeless flame, and has a high heat-producing capacity.

Coals of special types are formed from a variety of organic ooze rich in spores or algal remains. These contain less carbon than the normal coals of corresponding rank, but are notably richer in hydrogen. When heated they give off abundant supplies of hydrocarbons and on distillation they yield oil. Varieties in which algal remains predominate are called *boghead coals*, or *bogheads*, after the name of an estate in West Lothian where they were first mined. They are close grained and tough and often resemble dark brown or nearly black leather. They leave a considerable residue of ash, most of which is the muddy material that contaminated the original ooze. By increase of inorganic sediment the bogheads pass into *oil-shales*.

Between bituminous coal and the bogheads there are intermediate varieties known as *cannel coal*. In some of these spores and blebs of resin are very abundant, while others contain algal remains in addition. Cannel coal is dull black and appears quite structureless to the unaided eye. It occurs as individual seams and also as lenticles and bands in seams of ordinary coal. The name refers to the fact that splinters of cannel can be burnt like a candle, a fact that in turn demonstrates the richness of the material in inflammable hydrocarbons.

The Constitution of Coal

Almost any block of bituminous coal can be seen to have a well-marked banded or stratified structure. The commonest bands are composed of soft bright coal which readily breaks into approximately right-angled pieces with smooth brilliant surfaces. Most of the bands appear to be quite structureless,

and since the material bears a close resemblance to glass it has been called *vitrain* or *vitrinite*. Others are finely laminated and consist of shreds and films of vitrinite in a very fine-grained matrix. This type of coal material is known as *clarain*. The bands of bright coal are separated by layers of a dull grey-black type of coal which, being relatively hard and tough, is distinguished as *durain*. None of the three types already mentioned soils the fingers. The dirtiness of coal is due to the presence in quite small amounts of a fourth type of material called *fusain* or *fusinite*. It consists of thin flakes of extremely friable " mineral charcoal " which are distributed over certain surfaces at intervals through the seam. Coal naturally splits very easily along these surfaces, and as the fusinite readily crumbles to powder the broken coal becomes dusty.

All the types of coal are intensely opaque, and it is necessary to make sections ten times as thin as those of ordinary rocks before light can penetrate the material so that microscopic examination becomes possible. A translucent film of vitrinite 1/10,000th of an inch in thickness is no longer black, but has a rich golden brown or reddish colour. It is found to consist of bark or wood, each band representing a single fragment. Section A of Plate 76 shows a highly magnified sample of typical vitrinite in which the cellular structure of bark is perfectly preserved. The material clearly corresponds to the humified bark found in peat.

Fusinite, similarly examined, also turns out to be wood or bark, but only the carbonized cell walls remain, the cells being empty or occupied by ash. It represents woody and other fibres that escaped humification, though how they became altered into charcoal is a problem that remains unexplained. Some of the fusinite may be the charred relics of forest fires, but most of it appears to have been formed after burial during the process of " coalification."

Unlike these two types, which are unit constituents of uniform composition, durain is found to be an assemblage of minute particles, like the organic ooze of peat. It contains the resistant coats of spores, more or less crushed and flattened, microscopic shreds of vitrinite, lenticles and grains of fusinite,

and blebs of resin, in an obscure matrix of debris too finely macerated to be identified. Section B of Plate 76 is cut from a band of dull spore-coal, and shows durain consisting of microspores (male) and macrospores (female) embedded in a dark matrix. In Section C, cut from a banded coal, the upper portion is part of a band of durain showing the same features. The lower middle portion is a band of vitrinite formed mainly from compressed bark. Part of another band of durain, with microspores, is seen below.

Clarain contains the same ingredients as durain, but in very different proportions. The well laminated structure and brightness are due to the presence of abundant closely packed strips of vitrinite. The intervening laminæ of durain-like material are extremely thin. A very highly magnified thin section of clarain would thus have an appearance not unlike the more coarsely banded coal illustrated in Plate 76C. Clarain, indeed, is a sort of microscopic replica of a seam of bright coal in which bands of vitrinite predominate.

Cannel coal is essentially durain which is especially rich in spore cases and other waxy and resinous remains. There are transitional varieties towards clarain on the one hand and towards the algal-rich bogheads on the other.

Lignites and anthracites are found to consist of the same structural types of material as bituminous coals. The variation in properties throughout the series depends partly on the proportions in which the type ingredients are present, and partly on the degree of alteration which they have suffered, *i.e.* on the rank of the coal. Fusinite, for example, is highly inflammable, because its friability and high porosity make for easy oxidation. Coal-dust explosions—formerly a serious menace to mining before precautions were enforced—result from this dangerous property. Spore cases and resins are rich in hydrocarbons ; consequently dull coals and cannels yield far more gas and tar than the bright coals of intermediate ranks. The latter, however, are excellent for household purposes. Steam coal, suitable for use in locomotives and ships, is of higher rank, transitional towards anthracite. It burns with little smoke, but ignites more easily than anthracite and has a

high heat-producing capacity. The properties of anthracite—slow ignition and slow burning, with intense heat and no smoke—are determined entirely by its high rank. Even such spores as may still be detectable have been reduced to ghostly carbonized relics.

Coal Seams and Coalfields

The essential conditions for the development of a coal seam are (*a*) long-continued growth of peat ; and (*b*) subsidence of the area and burial of the peat beneath a thick accumulation of sediments. The peak period of coal formation was the Upper Carboniferous. Hercynian movements then provided the extensive, rhythmically subsiding basins in which the sediments and coal seams of the Coal Measures were deposited ; and provided them, moreover, along a belt running through North America (bordering the Appalachians), the British Isles, and parts of Europe and Asia, where the climate was then hot and the vegetation luxuriant.

There are no coalfields earlier than the Carboniferous. Land plants capable of preservation make their first feeble appearance only towards the end of the Silurian. By Carboniferous times, however, a rich and prolific flora had developed, and the fossilized remains of more than three thousand species are already known. The chief coal-makers were tall forest trees (*Lepidodendron* and *Sigillaria*, with widely spreading roots known as *Stigmaria*) which grew to heights of as much as a hundred feet ; and giant reeds called *Calamites* (the ancestors of the little horse-tails of to-day) which flourished in bamboo-like thickets to a height of fifty feet or more ; together with an undergrowth of smaller rushes and ferns, and slender plants of trailing or climbing habits (Fig. 179). No flowers or birds enlivened these gloomy jungles, but insects—again of extravagant size—were abundant.

Practically all seams of bituminous coal and anthracite have certain characteristics which are consistent with the theory that each seam represents the actual site of the swamp in which the parental vegetation lived and died.

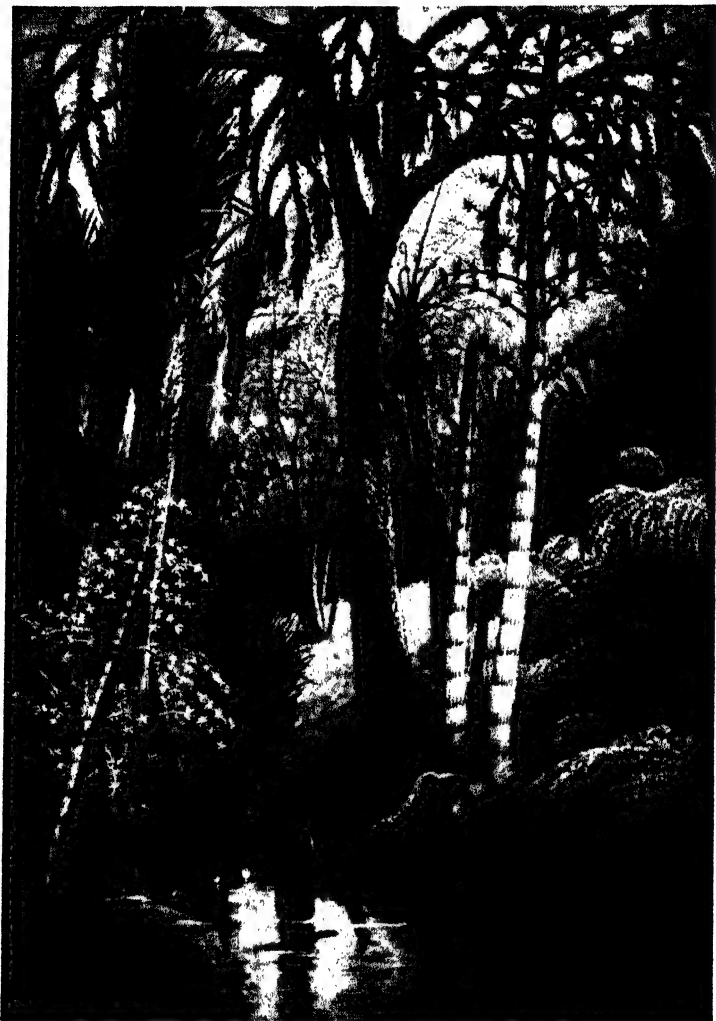



FIG. 179
Reconstruction of a Carboniferous forest

(*a*) The " seat earth " which forms the floor of a seam is a high-grade fireclay (useful for making refractory bricks). It is riddled with innumerable rootlets of the plants which first colonized the swamp, and may even contain casts of stigmarian

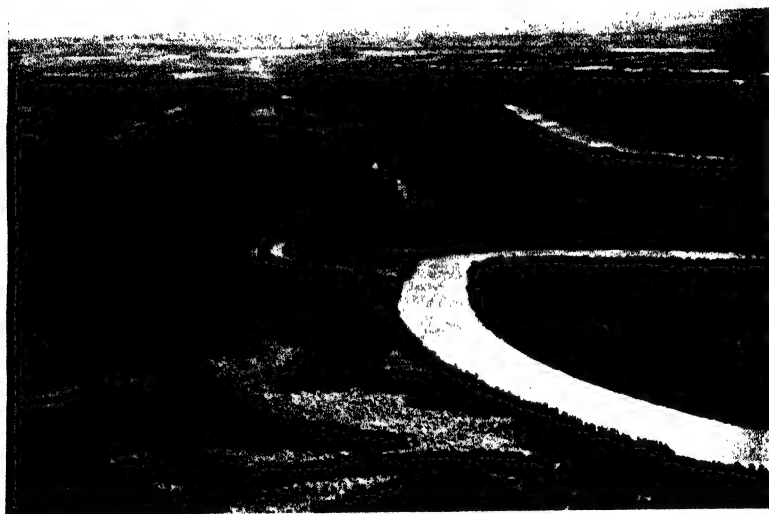
[H.M. Geol. Survey

(A) Remains of pine forest, exposed by removal of peat, near Daless, Findhorn Valley, Nairn

[J. R. Stewart

(B) Remains of Carboniferous forest (fossil trunks of *Lepidodendron* rooted in shales), Victoria Park, Glasgow

Dorien Leigh, Ltd.

(A) Aerial view of the Sudd on the Nile, Anglo-Egyptian Sudan

[From Burma Forest Bulletin No. 11, by permission

(B) Aerial view of forest, swamps, and creeks, Irrawaddy Delta, Burma

roots, often in the position of growth. The trunks either rotted away above water level or fell into the swamp to contribute to the lower part of the seam.

(*b*) The roof of the seam sometimes contains casts of the trunks of great forest trees. These represent the generation that was drowned when the swamp conditions were brought to an end, for the time being, by subsidence and general inundation.

(*c*) Seams are generally of very wide extent, sometimes covering areas of thousands of square miles with but little variation in thickness.

(*d*) Seams are locally interrupted by " wash-outs," that is, by the sandstone-filled channels of streams that flowed through the forest swamps, like the distributaries of modern deltas.

(*e*) The coal contains no fish remains or other fossils of aquatic animals, and (except in certain bands of durain) is uncontaminated by muddy sediment. Such ash as remains when the coal is burnt is derived either from the vegetation itself or from carbonate minerals and pyrite (the brassy-looking material sometimes seen in coal) subsequently deposited in cracks from ground-waters. Seams and bands of the durain type may, however, leave a little sedimentary ash. These dull coals seem to have accumulated in stretches of stagnant water into which a limited amount of fine sediment might be introduced while the delta rivers were in flood.

In the special coals—the cannels and bogheads—muddy sediment is much more abundant than in durain. Moreover, these varieties contain the remains of fish and other aquatic organisms. The water in which the mud-contaminated ooze accumulated was therefore not stagnant, but was continually renewed and oxygenated. Evidently these coals were formed not *in situ*, but from plant debris that was drifted by wind and running water into lakes with a through drainage. Such conditions would also arise locally in the hollows of a peaty surface just beginning to subside. Matching expectation, thin lenticles of cannel of limited area are found to occur at the top of many seams of otherwise normal coal.

FIG. 180

Map of the coalfields (black) of the British Isles. Areas of younger rocks are indicated by shading; those of older strata are left unshaded. (The leading tectonic structural lines of Scotland and their continuations into Ireland are added for convenience; see pp. 367 and 436)

In the Upper Carboniferous coalfields the successive seams are separated by a characteristic sequence of sediments which is commonly repeated dozens of times, and in some localities hundreds of times. A coal seam is usually roofed with shales in which fossil leaves and bands of freshwater mussels fre-

quently occur. As they are followed up the shales become sandy and pass into sandstones, sometimes with shaly interruptions. Then follows the seat earth that underlies the next coal. The picture is clearly one of repeated alternations of phases of subsidence and phases of comparative rest.

The subsiding regions developed into widespread tectonic basins lying between rising tracts of country which supplied the basins with sediments and kept them filled. The floor of part of the South Wales coalfield sank more than 10,000 feet in all, while to the north a persistent ridge of higher ground separated the southern basin from the vast area of irregular depression in which the northern coalfields originated (Fig. 180). The sediments of this group of coalesced basins came mainly from an upland region now represented in part by the Highlands of Scotland.

Evidently at this time both the British area and the adjoining parts of Europe (Fig. 200) were being warped into basins and swells by pulsations of pressure associated with the Hercynian mountain-building movements. The latter were already in active progress farther south. By later movements the basins and their contents were themselves buckled, folded, and faulted. The dominantly upfolded portions, being exposed to denudation, have since lost their original covering of Coal Measures. The downfolded portions, however, have been preserved as the isolated coalfields of to-day; either where the Coal Measures are exposed at the surface, or, like the coalfield of Kent, where they are concealed by a blanket of later deposits.

PETROLEUM

Petroleum (Gr. *petra*, rock, L. *oleum*, oil) is the general term for all the natural hydrocarbons—whether gaseous, liquid, or solid—found in rocks. In common usage, however, it refers more particularly to the liquid oils. Gaseous varieties are distinguished as *natural gas*. Highly viscous to solid varieties are called *bitumen* or *asphalt*, but the latter term is also applied to the

bituminous residues left when petroleum is refined, and to natural and artificial paving materials composed of sand, gravel, etc., with a bituminous cement.

Petroleum consists of an extremely complex mixture of hundreds of different hydrocarbons, generally accompanied by small quantities of related compounds containing nitrogen, sulphur, or oxygen. The hydrocarbons fall into a number of natural series of which the paraffin series is the most familiar. Its members, all of which can be expressed by the formula C_nH_{2n+2}, range from light gases (*e.g.* methane, CH_4, the chief constituent of natural gas), through a long series of liquids (the chief ingredients of successive products of distillation such as petrol, paraffin oil, and lubricating oil), to paraffin wax (including $C_{20}H_{42}$ and higher members). Crude oils in which these hydrocarbons predominate are said to have a paraffin base ; they are generally of pale colour with a yellowish or greenish hue. The darker brown and greenish oils generally contain a high proportion of the naphthene series, each member having a composition of the type C_nH_{2n}. These furnish heavy fuel oils and, as they leave a dark asphaltic residue on being refined, they are said to have an asphaltic base. Intermediate varieties have a mixed base of wax and asphalt. In all crude oils there are also smaller proportions of several other series, including acetylene and its higher members, C_nH_{2n-2}, and a great variety of aromatic hydrocarbons, of which the benzene series, C_nH_{2n-6}, is an example.

To avoid confusion it should be clearly understood that neither oil shales nor the cannel and boghead coals contain petroleum as such. If they did, it could be dissolved out by carbon disulphide. They do, however, contain *pyro-bituminous* substances which can be altered into oil and bitumen by heat. Such deposits can therefore be made to yield a group of petroleum products by destructive distillation. Petrol and related products can be obtained in commercial quantities from ordinary coal only by highly technical processes involving the intimate introduction of hydrogen into suitably prepared coal at high pressures and temperatures. Petrol can also be

made from the heavier and less valuable oils by a similar but less elaborate process of hydrogenation. The following table summarizes the sources of oil and related products :

Bituminous deposits of Petroleum	*Pyro-bituminous deposits requiring destructive distillation*	*Carbonaceous deposits requiring hydrogenation*
Natural gas Crude or mineral oil Bitumen and mineral wax	Special Coals : Cannels Bogheads	Ordinary coals
Tar sands and asphalt	Oil-shales	—

Being fluids, oil and gas behave very much like ground-waters. They occupy the interstices of pervious rocks, such as sand and sandstone and cavernous or fissured limestones, in places where these " reservoir rocks " are suitably enclosed by impervious rocks, so that the oil and gas remain sealed up. Accumulations on a scale sufficient to repay the drilling of wells are referred to as oil or gas pools. The " pool," however, is merely the part of a sedimentary formation that contains oil or gas instead of ground-water.

The Origin of Petroleum

Unlike coal, petroleum retains within itself no visible evidence of the nature of the material from which it was formed. It has been suggested as a purely speculative possibility that oil may have been formed by volcanic or deep-seated chemical processes akin to the production of acetylene by the action of water on calcium carbide. But these hypotheses are quite incompatible with the geological distribution of oil and with certain peculiarities of its composition and properties. All the relevant evidence points convincingly to an organic origin.

(*a*) Some of the constituents of petroleum have the property of altering the direction of vibration of light rays. This " optical activity " is characteristic of certain substances pro-

duced by plants and animals, but is not shared by the hydrocarbons and related compounds generated by purely chemical reactions.

(*b*) The nitrogen-bearing constituents of petroleum include a group of compounds called *porphyrins* which can be formed only from the green colouring matter (chlorophyll) of plants or from corresponding colouring substances of animal origin. Oil-shales rich in algal remains also contain vegetable porphyrins. In the presence of oxygen the porphyrins are quickly destroyed, and their persistence in oil indicates that the latter must have originated in an environment from which free oxygen was absent. Although the porphyrins derived from vegetation are more easily oxidized than those of animal origin, they are, nevertheless, the dominant type. It is therefore probable that plant life has contributed to the raw material of petroleum more than animal life.

(*c*) Oil is not found in association with volcanoes or igneous rocks, except accidentally. West of Edinburgh, for example, oil shales have been invaded by intrusions and volcanic necks, with results comparable to those obtained when oil shales are distilled. Oil so liberated by metamorphism would naturally migrate into overlying sandstones, and there it is still occasionally found. No major oilfield, however, has originated in this way. About 70 per cent. of the world's known oilfields have been located in marine sediments of Cretaceous and Tertiary age, generally along the flanks and in the less closely folded portions of the Tertiary orogenic belts. Most of the remaining fields occur in the Palæozoic sediments of North America and the U.S.S.R. in the geosynclines and marginal basins of earlier ages (*cf.* Fig. 182). No oil pools of commercial importance have been found in sediments older than the Ordovician.

(*d*) The existence of pre-Carboniferous oilfields suggests that land plants were not essential to oil formation, and this inference is strengthened by the important fact that no significant lateral connection between coal seams and oil pools has anywhere been traced. The two may occur in close association

by some accident of faulting, and one may lie above the other in a sequence of varied strata, but in neither case has the association any bearing on the origin of oil. While it is not impossible that drifting relics of land vegetation, swept into the sea by great rivers, may have contributed to oil formation, it is likely that such a source was quite subsidiary to the contributions furnished by marine algae and diatoms. Moreover, wherever the conditions were such that organic residues from marine plants could survive, they must equally have favoured the accumulation of similarly unconsumed remains of foraminifera and other forms of animal life.

The various lines of evidence all lead to the conclusion that petroleum has originated from organic matter which became incorporated in the sediments of depressed regions of the sea floor. The organisms flourished in the surface waters, and their dead remains sank into stagnant depths with a marked deficiency of oxygen, where bacteria alone could live, and where they were safeguarded from being either oxidized or eaten. Indeed, under these conditions oxygen would be actually abstracted by bacteria, and the organic matter transformed into fatty and waxy substances. For an example of the early stages of oil formation, in progress at the present day, reference may be made to the muds now collecting in the deeper parts of the Black Sea. Samples dredged up contain as much as 25 per cent. of organic matter, and 10 per cent. of this has already been changed into heavy hydrocarbons, soluble in benzene. The solution, moreover, is green and contains traces of chlorophyll. The oil first generated in mud is mainly bitumen composed of large molecules. The lighter hydrocarbons of the paraffin series appear to be later derivatives, produced by a kind of natural refining brought about during burial by increased pressure, rising temperature and continued bacterial action. Bacteria are known to exist in the ground-waters of certain oilfields. The details of those later developments are, of course, very difficult to trace.

Migration and Concentration of Petroleum

The sediments in which petroleum had its origin are called the *source rocks*, to distinguish them from the *reservoir rocks* in which oil and gas are now found on a commercial scale. The reservoir rocks carry far more oil than could possibly have originated within them and, moreover, they commonly contain fossils of the benthos group which lived on the bottom in shallow oxygenated waters where no appreciable quantities of organic matter could have survived. The source rocks, on the other hand, must have been muds and calcareous deposits with fossils, when preserved, corresponding to the organisms (mainly of the plankton group) which contributed the raw materials of petroleum. An oil pool is, in fact, a concentration of oil which has migrated from the source rocks into places where it could draw to a head and accumulate.

Source beds such as clay and shale are now compact and impervious. But while they were still unconsolidated they contained a high proportion of sea-water carrying dispersed globules of oil. During this stage circulation of the mixed fluids would sooner or later become possible, in response to pressure differences set up by a varying overhead load or, more effectively, by earth movements. As the source beds become compressed, the squeezed-out fluids pass into more coarsely porous and less compressible formations, such as sands. Once the oil has been flushed into these permeable beds it may be carried through them for long distances, but it cannot again escape from them, unless the overlying rocks are fissured. If the mixed fluids encounter a sediment with very fine pores, the water may filter slowly through, but the oil is held back. Within the sand or other reservoir bed the oil trickles upwards through the water until it comes up against an impervious barrier and collects there.

In general, then, oil migrates outwards and upwards from the source beds, passes into coarsely porous or fissured reservoir beds, rises to the highest possible level, and collects into an oil pool wherever the structure provides a trap which impedes further migration. Gas, if present in excess of the amount

that the oil can hold in solution, bubbles to the top and forms a *gas cap* over the pool. Beneath the pool the pore spaces are occupied by ground-water (often salt) which is commonly under a very considerable hydrostatic pressure. If the pressure and gas content are sufficiently high, the oil gushes out like an effervescent fountain when the pool is tapped by drilling. But when the pressure conditions are insufficient to drive the oil to the surface—or become so as the initial pressure falls off—pumping is necessary to bring it up.

In accordance with the principles of oil concentration a dome or anticline of alternating pervious and impervious sediments makes an efficient trap for oil migrating towards it (Fig. 181*a*). Isolated open anticlines surrounded by extensive gathering grounds have a much better chance of being productive than more closely packed folds. Not only have the latter to share a limited supply, but they are likely to be too much broken and fissured to retain any oil and gas that passed into them.

Although the " anticline theory " of oil concentration dominated the search for oil for many years, it gradually came to be realized that anticlines are far from being the only traps, or even the most productive. The early discovered oil-fields of Pennsylvania, for example, occur in a broad sedimentary basin in which the formations still remain practically horizontal over widespread areas. Here the oil pools occupy lenticular bands of porous sandstone which pass laterally, as well as vertically, into shales ; thus the oil is sealed within an impervious envelope (Fig. 181*c*). Oil pools occupying the upper ends of tilted reservoir beds are also of great importance. The tilted bed may pass laterally into shale, or it may be more abruptly cut off by an impervious barrier. The obstacle may be a fault throwing an impervious bed against the reservoir bed (Fig. 181*b*) ; or a hill belonging to an ancient land surface which was unconformably overlapped and buried by a later series of petroliferous strata (Fig. 181*d*) ; or a salt dome which has been intruded into a thick series of sediments (Fig. 181*e*).

Salt domes are curious structures occurring in great

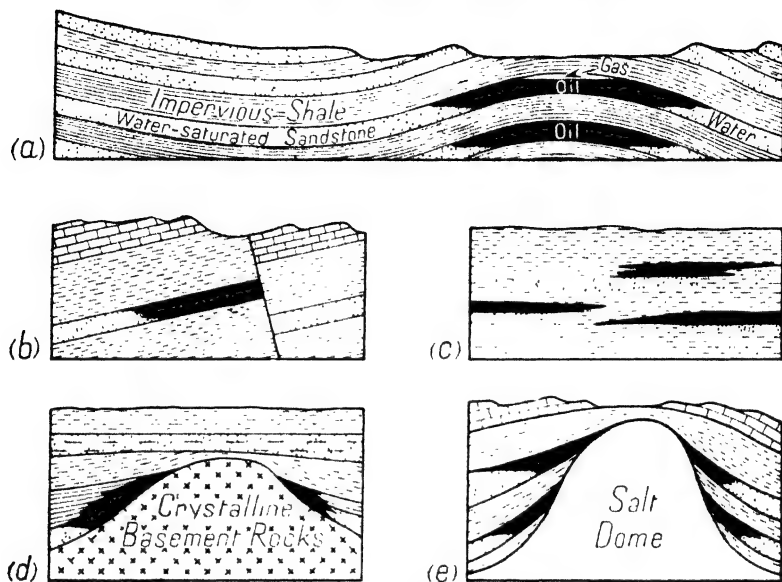



Fig. 181
Sections to illustrate various types of structural traps favourable to the accumulation of oil and gas (gas is omitted except in *a*)

numbers along the Gulf Coast of the United States and in other regions where salt deposits have been deeply buried. Being plastic under high pressure, the salt is squeezed towards places of weakness in the sedimentary cover. It then develops into a plug which ascends through the cover, perforating and doming up the beds as it advances. Some salt domes rise from depths of four or five miles. In Iran some of them bulge up the surface, and those that are still actively rising pierce the roof and escape down the slopes as " glaciers " of salt. The simple case illustrated in Fig. 181*e* shows oil accumulating against the walls of a salt dome. Oil may also be dammed back by faults produced in the surrounding rocks by the upward drag of the intrusive salt, and finally, it may collect in the domed sediments over the roof.

Oil is not necessarily, or even generally, confined to a single reservoir bed in a given field. Any suitably placed formation may have been fed either from an outlying primary source, or

via an underlying pool, the oil from which escaped upwards through fractures in the intervening impermeable beds. Gas, in particular, readily migrates to higher levels, and in many places vast quantities occur alone. This reflects the natural tendency of some varieties of petroleum to differentiate into asphaltic and gaseous fractions. If the reservoir begins to leak after such fractionation has taken place, the mobile gas moves on and leaves the sticky asphalt behind. Most of the gas encountered by drilling was formerly discharged into the air and wasted. But now it is welcomed, not only as an easily distributed source of power and illumination, but still more because its heavier constituents can be condensed into petrol.

The Discovery of Oilfields

Wherever the cover of a reservoir is perforated by fissures leading up to the surface, leakage of gas and oil becomes inevitable. Moreover, denudation may strip off the covering rocks until gas can force a passage through the roof and so open a way for the subsequent escape of oil. Thus the most obvious indications that a region is petroliferous are (*a*) seepages and springs of gas or oil ; and (*b*) superficial deposits or veins of asphalt and other more or less " solid " residues of petroleum left behind after the volatile constituents have evaporated.

Inflammable gas may be found bubbling through the water of springs and wells or streams. In a few places gas escapes on a more spectacular scale. Historical records show that vigorous gas jets may persist for many centuries. Blazing jets, like the " perpetual fires " along the Caspian coast near Baku, were long regarded with veneration by Fire Worshippers. Where gas erupts through water-bearing strata and clays it carries up wet mud and spatters it around the vent until a mound is built up with a crater at the summit. Groups and rows of these " mud volcanoes," occurring on the crests of anticlines or along faults, are well known in Burma, Trinidad, California, and various other localities. Eruption may be continuous or spasmodic, according to the gas pressure and

the nature of the obstruction to be overcome. There is, of course, no connection with ordinary volcanic activity.

Flowing springs of oil emerge at the surface in some localities, but more commonly the exudations are sluggish, and the oil may be seen only as iridescent films on water. The largest surface "shows" are sands cemented with residual "tar" (bitumen), or localized deposits of more concentrated asphalt. These residues may eventually plug up the outlets and so prevent further losses from depth ; but, on the other hand, they may be all that remains of an otherwise dissipated oil pool.

Evidence of the use of bitumen in Mesopotamia dates back to very ancient times. Long before Noah caulked his Ark with asphalt, the value of bitumen for cementing and waterproofing purposes had become familiar to the Sumerians (4000 B.C.). The whole region of the Middle East, from the Caucasus to Iran, is now known to be richly endowed with concentrations of oil. The famous asphalt lake of Trinidad, first described by Léry in 1786, is still being replenished from underlying oil sands, but much too slowly to keep pace with the immense quantities removed each year. Another well-known occurrence is near Los Angeles, where crater-like depressions blown out by gas have been filled with deposits of asphalt. Here the skeletons of a great variety of prehistoric animals are found in a perfect state of preservation, their unfortunate owners having broken through the surface crust and become helplessly mired.

The first oilfields to be discovered were naturally found by digging wells in the neighbourhood of surface "shows." Many centuries before the Yenangyaung field of Burma (Plate 77A) was developed by modern methods the Burmese collected oil from surface exudations and later from shallow hand-dug wells. Yenangyaung is the classic example of the concentration of oil in the sands of an elongated dome. Oldham was the first geologist to survey the area, and as early as 1855 he pointed out the importance of anticlinal structures as oil traps. Nevertheless little call was made on the services of geologists until after 1900, when the demand for oil began to accelerate, first for motor transport, then for aeroplanes, and eventually for war purposes and national security. It was then

realized that the systematic discovery of oil involves the search for potential oil traps, that is to say, it demands the detailed geological survey of all the regions in which oil might conceivably lie hidden. The search for oil became a geological enterprise.

It is obvious, however, that in addition to the favourable structures that can be located from outcrops at the surface, there must be some that cannot be detected in this way, and others that lie concealed by tropical forests or marshes, by spreads of alluvium, boulder clay, desert sands or loess, or even by the sea. Hidden anticlines and structures such as the buried hills and salt domes illustrated in Fig. 181 can be detected by the gravity anomalies (p. 404) to which they give rise. Significant structures of all kinds can be explored by their effects on artificial earthquake waves (p. 371). Such waves are generated to order by exploding a charge of dynamite in the ground, and the waves reflected or refracted back to the surface by the rocks encountered in depth are then recorded by seismographs placed at suitable distances from the point of explosion. Many hundreds of salt domes, for example, have been successfully located by this method. Magnetic and electrical methods of exploring underground structures have also been devised.

The discovery of a favourable structure does not, of course, guarantee that oil will be found. On the other hand, the absence of surface indications is no proof that oil will not be found ; it may also mean that the oil, if there, is sealed in so efficiently that it cannot escape. Whether oil is present in commercial quantities or not can be finally determined only by the practical test of sinking wells to strike the parts of the suspected reservoirs where oil is most likely to be concentrated.

In the early days of the oil industry a few important oil-fields were found more or less by accident. Wells drilled for water, for example, sometimes strike oil. Moreover, there have always been optimistic operators willing to risk their capital and take a chance by sinking " wildcat " wells on sites selected for some quite unscientific reason. Only 3 or 4 per cent. of these speculative ventures have proved successful, but the

fabulous profits that reward success continue to encourage wildcat prospecting. It is a remarkable fact that the first indication of the existence of a great oilfield in East Texas was discovered in 1930 merely by drawing a line between two of the already developed fields of Texas and Louisiana and drilling along it. In twelve years this prolific field produced over 300 million tons of oil from about 30,000 wells in an area of 7 miles by 40, and it will probably yield at least as much again before it is exhausted. This is a world record so far.

The following production figures for the last full year before the War serve to illustrate the general distribution of oil by countries :

PETROLEUM PRODUCTION (IN TONS) IN 1938

Country	Tons	Country	Tons
U.S.A.	167,705,000	Peru	2,186,000
U.S.S.R.	29,630,000	Burma and India	1,435,000
Venezuela	27,657,000	Bahrein	1,117,000
Iran	10,192,000	Canada	883,000
Dutch East Indies	8,194,000	Germany	599,000
Rumania	6,761,000	Poland	541,000
Mexico	5,434,000	Japan	344,000
Iraq	4,298,000	Equador	291,000
Colombia	3,068,000	Egypt	222,000
Trinidad	2,541,000	All other countries	321,000
Argentina	2,386,000		
		Total	275,805,000

The total world production up to the end of 1938 is estimated to have been about seventeen times the 1938 total, and the proved reserves at that date amounted to about sixteen years' supply at the 1938 rate of extraction. However, as new fields are continually being discovered, it is not likely that any serious shortage of oil will be felt for many years to come.

A particularly significant fact is that 54 per cent. of all the oil already won has been contributed by the United States, although its territories include only 15 per cent. of the world's total area of unmetamorphosed marine sediments of Palæozoic and later ages in which oil might be expected to occur. Let us call 54/15 or 3·6 the relative productivity of the United

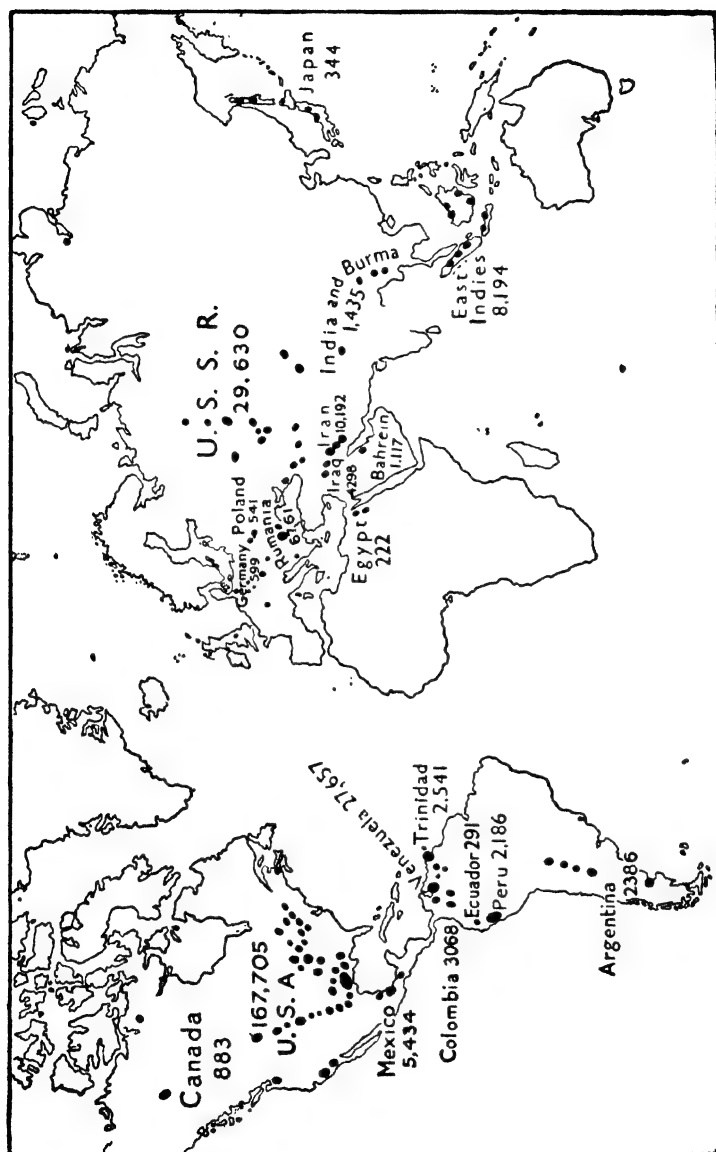



Fig. 182

Map showing the distribution of the chief oilfields, with production figures by countries in 1938 (in thousands of tons)
(*After G. M. Lees*)

States. Then the corresponding productivity for all the rest of the world is 46/85 or 0·54. This means that seven times more oil has been obtained from the marine sediments of the United States than from the similar sediments elsewhere. Yet from a geological point of view there is no obvious reason why the United States area should have been so specially favoured.

It may be conceded as probable that the United States has more than an average share of the world's oil, but it must not be overlooked that its citizens have sought for oil far more actively than those of any other country. Geologists have been employed in making systematic surveys on a scale rivalled only by Britain and the U.S.S.R. (who, however, began late) and the efforts of wildcatters have provided much additional information, as well as a surprising amount of oil, despite the wastage of effort involved in the attempt to short-circuit the preliminary search for structures. Altogether more than a million wells have already been drilled and the number grows by about 30,000 a year. Moreover, as the shallow pools became exhausted, wells have been sunk to ever-increasing depths. One exploratory well in California has been carried down just over 15,000 feet. In the light of this record of enterprise it is impossible to resist the conclusion that the high rate of oil production and discovery in the United States reflects the intensity of the search as well as the actual resources. It may not unreasonably be anticipated that other lands favoured with suitable sediments and structures may yet be rewarded with successful discoveries when the problem of finding oil is tackled with corresponding energy and efficiency.

SUGGESTIONS FOR FURTHER READING

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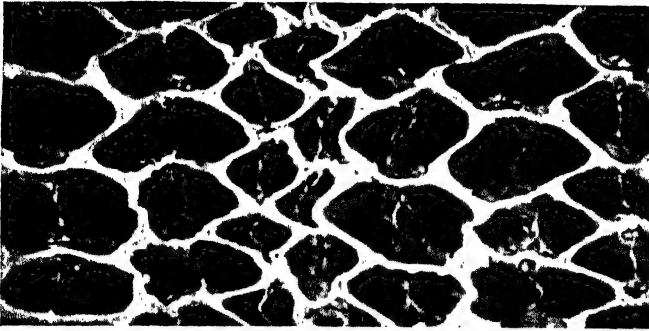

[C. E. Marshall

(A) Bark preserved as vitrinite. × 350

[C. E. Marshall

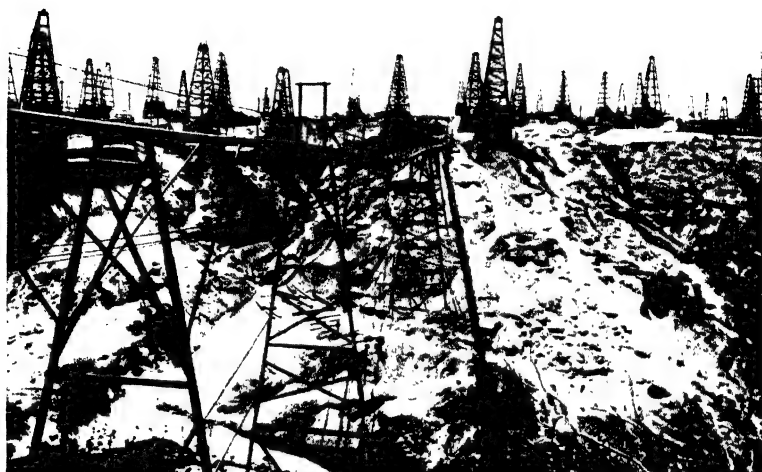
(B) Dull coal (durain) with spores. × 30

[C. E. Marshall

(C) Normal banded coal. × 30

PHOTOMICROGRAPHS OF COAL

PLATE 77

[L.N.A.

(A) Part of the Yenangyaung Oilfield, Burma (in 1922)

[*Burmah Oil Co., Ltd.*

(B) Part of the Digboi Oilfield, Assam

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PART III—INTERNAL PROCESSES AND THEIR EFFECTS

Chapter XVII

EARTHQUAKES

The Nature of Earthquakes

When a stone is thrown into a pool, a series of waves spreads through the water in all directions. Similarly, when rocks are suddenly disturbed, vibrations spread out in all directions from the source of the disturbance. An earthquake is the passage of these vibrations. In the neighbourhood of the disturbance itself the shaking of the ground can be felt and the effects may be catastrophic, but further away the tremors die down until they can be detected only by delicate instruments called seismographs (Gr. *seismos*, an earthquake).

Vibrations are set up in solid bodies by a sudden blow or rupture, or by the scraping together of two rough surfaces. Corresponding causes of earthquakes in the earth's crust are volcanic explosions, the initiation of faults, and the movements of the rocks along fault planes. Perceptible tremors are set up by the passage of trains and tanks, by avalanches and landslides, by rock falls in mines and caverns, and by explosions of all kinds. When a munition factory explodes, the intensity of the resulting earthquake may be comparable with that of volcanic earthquakes. The majority of earthquakes, however, including all the most widespread and disastrous examples, are due to sudden earth movements, generally along faults ; these are distinguished as *tectonic* earthquakes. The term *tectonic* (Gr. *tekton*, a builder) refers to any structural change brought about by deformation or displacement of rocks (*cf.* architecture).

The cause of tectonic earthquakes is thus the application of stresses to rocks until they are strained to breaking point,

when they suddenly rupture and move. The fault movements themselves, as already described on page 78, may be either vertical or horizontal or oblique. After the great Alaskan earthquake of 1899, it was possible from the presence of barnacles clinging to the uplifted rocks of Disenchantment Bay to measure the uplift, which in this case reached an exceptional maximum of 47 feet. In Japan the crustal blocks

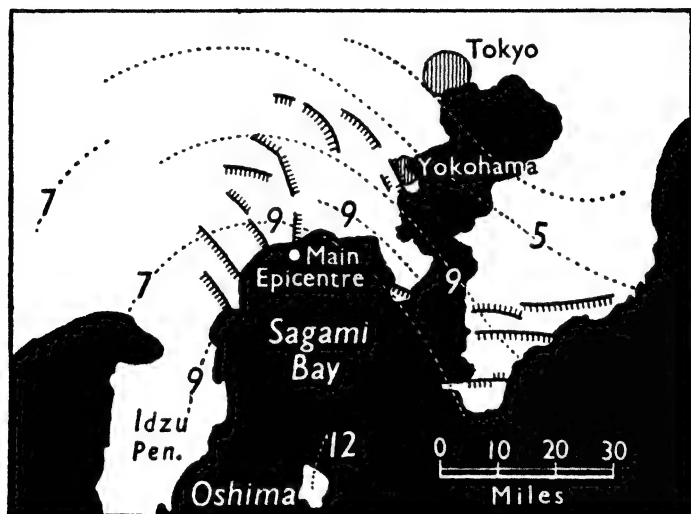



FIG. 183

Map of Sagami Bay, Japan, showing movements associated with the earthquake of September 1, 1923. Vertical displacements ranging from a few inches to several feet are indicated by shading on the downthrow side of the fault lines. Horizontal rotation in a clockwise direction is indicated by dotted lines, with numbers representing the displacement at various localities in feet

often move obliquely, both vertical and sideways movements being observed. Surveys carried out after the Sagami Bay earthquake of 1923, when Tokyo and Yokohama were wrecked, showed that the floor of the Bay and the surrounding mainland had twisted round a little in a clockwise direction, the observed shift of Oshima Island being over 12 feet (Fig. 183). Both in Japan and the Philippines the horizontal fault displacements indicate a general southerly movement of the Pacific side. On the other hand, the horizontal movements along the San

Andreas fault in California point to a northerly movement on the Pacific side (Fig. 184). Along one stretch of the San Andreas fault, deep ravines in the hillsides on the continental side of the fault are abruptly displaced, reappearing on the seaward side 150 feet to the north-west. This probably represents the cumulative effect of several comparatively recent

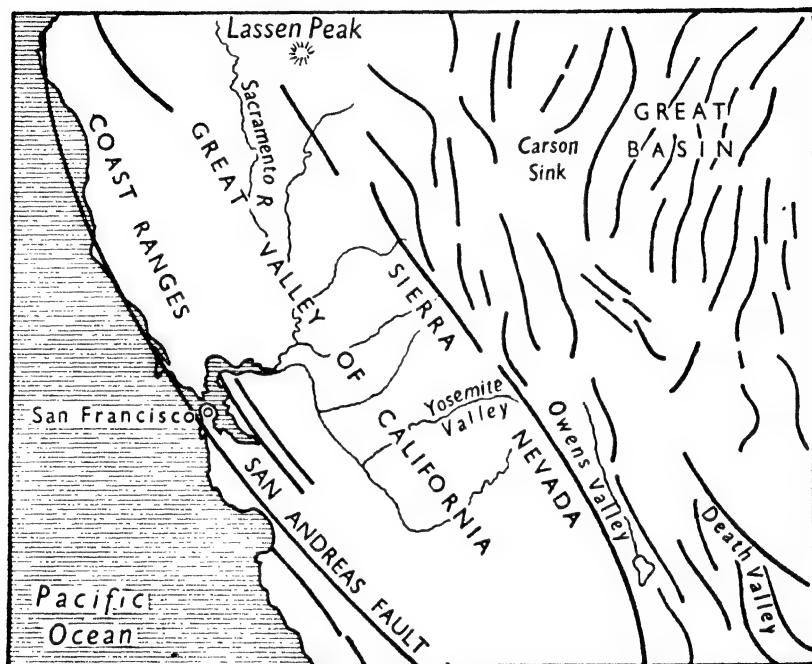



FIG. 184

Map of part of California and Nevada showing the San Andreas fault and the other chief faults of the area. Many of these have been active in recent time

fault movements, each like the one responsible for the 1906 earthquake when the maximum lateral shift was 21 feet.

When the rocks are nearly at their breaking point, an earthquake may be precipitated by some minor, but quite extraneous agent, such as a high tide, a rapid change of barometric pressure, or shaking by an independent earthquake originating elsewhere. Thus arises the occasional association

of earthquakes with great storms or with other earthquakes. The principal shock, which generally lasts only a few seconds or at most a minute or two, may be preceded by fore-shocks, and is invariably followed by a series of after-shocks. The fore-shocks represent the preliminary loosening and removal of small obstructions along a fault plane or zone. When these have been overcome, the main movement occurs. But complete stability is not restored immediately, and moreover, the jolt often disturbs adjoining fault-blocks. The after-shocks represent the minor movements as the region gradually settles down again. Considering the whole earth, earthquakes of one kind or another take place every few minutes, but many of these are so slight that they are known to have occurred only from instrumental records. Really severe earthquakes, which would be catastrophic in populated areas, take place about once a fortnight on an average. Fortunately most of these originate beneath the continental slopes and do little damage.

The Effects of Earthquakes

One of the most alarming and disastrous features of a great earthquake near its place of origin is the passage of large " surface " waves over the ground, which is thrown into ever-changing undulations. The latter may be only a foot high and 30 feet or so from crest to crest, but the rapidity of their rise and fall often gives the terrifying impression that the ground is writhing " like a storm-tossed sea." Fissures gape open at the crests, only to close again as the waves pass and the crests turn into troughs. Roads are cracked open (Plate 78A), railways are buckled and twisted (Plate 78B), bridges collapse (Plate 79), and buildings are shaken down. On the sea floor telegraph cables may be broken. The surface waves are a local by-product of the normal earthquake vibrations, which are of a much smaller order. In the Assam earthquake of 1897 the ground vibrated more than two hundred times a minute, each to and fro movement being more than a foot in range. Such rapid shaking through even an inch or two

would be highly destructive. A range of a quarter of an inch would suffice to wreck most buildings not specially constructed to resist earthquake shocks, and one of $\frac{1}{1000}$ inch can be felt. The effect on the feet of the vertical vibrations in a strong earthquake has been described as like the "powerful upward blows of a monstrous hammer."

In the region of destruction landslides are set moving on valley sides, and avalanches are started in snowy mountains. Glaciers are shattered and where they terminate and break off in the sea icebergs become unusually abundant. Vast masses of wet sediments may be so loosened by submarine shocks that they slump for miles down the continental slope. In Sagami Bay in 1923 parts of the floor were thus lowered by 1,000 to 1,500 feet, other parts being correspondingly raised. Underground water is greatly disturbed by earthquakes, and new lakes or swamps may be formed and old ones drained. Compression of water-filled sands, especially in alluvial districts, forces the water to ascend through fissures and often to issue at the surface in powerful sandy jets around which sand-craters develop.

Strong submarine earthquakes are followed by seismic sea waves, technically called *tsunamis* (Japanese). The celebrated Lisbon earthquake of 1755, probably the greatest on record, originated in a sudden subsidence of the sea floor to the west. At Lisbon the sea withdrew immediately after the principal shock, only to return as a gigantic wave, about 40 feet high, which swept across the lower parts of the city and completed the ruin and desolation. The ebb and flow of the sea continued for some time after the first wave, this being an inevitable characteristic of all tsunamis. The Lisbon earthquake was of such exceptional severity that lakes were set oscillating as far away as Loch Lomond and Loch Ness, where the water continued to rise and fall through a range of two or three feet for about an hour.

The appalling losses of human life that accompany great earthquakes in populated areas are mainly due to secondary causes such as the collapse of buildings, fires, landslides, and tsunamis. Gas mains are torn open and fires, once started,

rapidly spread beyond control, since the water mains are also wrenched apart. In San Francisco in 1906 far more damage was done by fire than by the earthquake itself. The Sagami Bay earthquake of 1923 occurred just as the housewives of Tokyo and Yokohama were cooking the midday meal. Fires broke out in all directions and completed the toll of death and destruction. Two hundred and fifty thousand lives were lost and over half a million houses destroyed. In the loess country of Kansu in China, 200,000 people were killed in 1920, and another 100,000 in 1927 by catastrophic landslips of loess which overwhelmed cave dwellings, buried villages and towns, and blocked river courses, so causing calamitous floods.

Isoseismal Lines and Depth of Origin

Within the area disturbed by an earthquake—which may be anything up to millions of square miles—the intensity at any place is gauged by the effects on buildings and on the ground (fissures and landslips), on people, and on seismographs. The intensity is stated by reference to an arbitrary scale of twelve degrees (originally ten), of which the following is a brief summary :

MODIFIED MERCALLI SCALE OF EARTHQUAKE INTENSITIES

I	(< 10)	*Instrumental*, detected only by seismographs
II	(> 10)	*Very feeble*, noticed only by sensitive persons
III	(> 25)	*Slight*, felt by people at rest
IV	(> 50)	*Moderate*, felt by people in motion
V	(> 100)	*Rather strong*, people are wakened, bells ring
VI	(> 250)	*Strong*, slight damage
VII	(> 500)	*Very strong*, cracking of walls, general alarm
VIII	(>1,000)	*Destructive*, chimneys fall
IX	(>2,500)	*Ruinous*, houses begin to fall
X	(>5,000)	*Disastrous*, many buildings destroyed
XI	(>7,500)	*Very disastrous*, few structures left standing, ground fissured
XII	(>9,800)	*Catastrophic*, total destruction, objects thrown into air, ground badly twisted

The actual intensity of the vibrations is measured by the maximum acceleration of the ground ; approximate values for the latter are given in each case in brackets (the acceleration of gravity in the same units is 9,800 mm./sec./sec.). From the centre of the disturbance the intensity decreases outwards inversely as the square of the distance.

A line drawn through all places with the same intensity

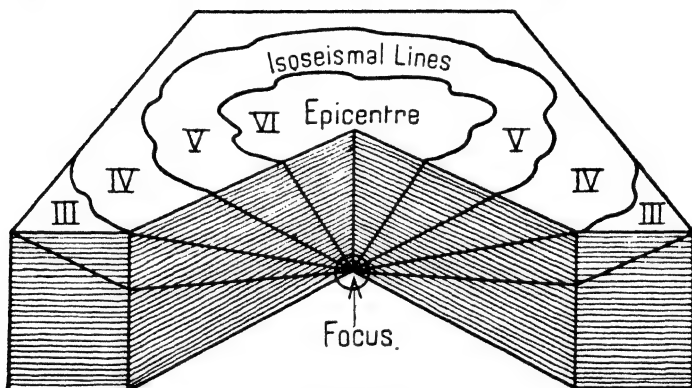



FIG. 185

Block diagram showing isoseismal lines and their relation to the epicentre and to the wave paths radiating from the focus of an earthquake

is an *isoseismal line* (Fig. 185). Each one generally encloses a roughly circular or elliptical area, according as the place of origin of the earthquake is a point-like or elongated area. The place of origin is called the *origin* or *focus*, and the point or line on the surface vertically above is the *epicentre* or *epicentral line*. By comparing the intensities at the epicentre and along an isoseismal line, Oldham showed how the depth of focus could be determined (Fig. 186).

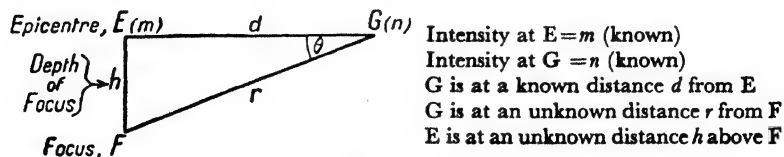



FIG. 186

Diagram to illustrate Oldham's method for estimating the depth of the focus of an earthquake

By the inverse square law,

$$n/m = h^2/r^2 = \sin^2\theta \text{ ; the angle } \theta \text{ being thus determined,}$$
$$h = d \tan\theta = \text{the depth of the focus.}$$

From the records of 5,605 shocks in Italy, Oldham found that 90 per cent. of the earthquakes originated at depths of less than 8 km. (5 miles) ; nearly 8 per cent. at depths between 8 and 30 km. ; and the rest at greater depths. Tectonic earthquakes are now classified as

Normal,	when the depth of origin is	0 – 50 km.
Intermediate,	when the depth of origin is	50 – 250 km.
Deep-focus,	when the depth of origin is	250 – 700 km.

Volcanic earthquakes, which may be due to gas explosions or to the formation and injection of fractures by magma, are generally of relatively shallow origin. For this reason the area of disturbance is correspondingly small (a few hundred square miles at the most), though the intensity may be high near the volcano.

Distribution of Epicentres : Earthquake Belts

Earthquakes may be recorded anywhere, but the places where they originate are confined to regions where earth movements or volcanoes are active. Fig. 187 shows the distribution of known epicentres during the present century. The distribution turns out to be essentially the same when all known epicentres are plotted and, moreover, the distribution of the most severe shocks corresponds closely with that of the most frequent. It will be noticed that most earthquakes originate in two well defined belts : a *Circum-Pacific belt* (68 per cent. of all earthquakes) with offshoots from Japan to Yap Island and from Central America through the West Indies ; and a *Mediterranean belt* (21 per cent. of all earthquakes) extending from the Cape Verde Islands and Portugal, through Asia Minor and the Himalayas to the Dutch East Indies, with a side branch from Tibet through China. Only 11 per cent.

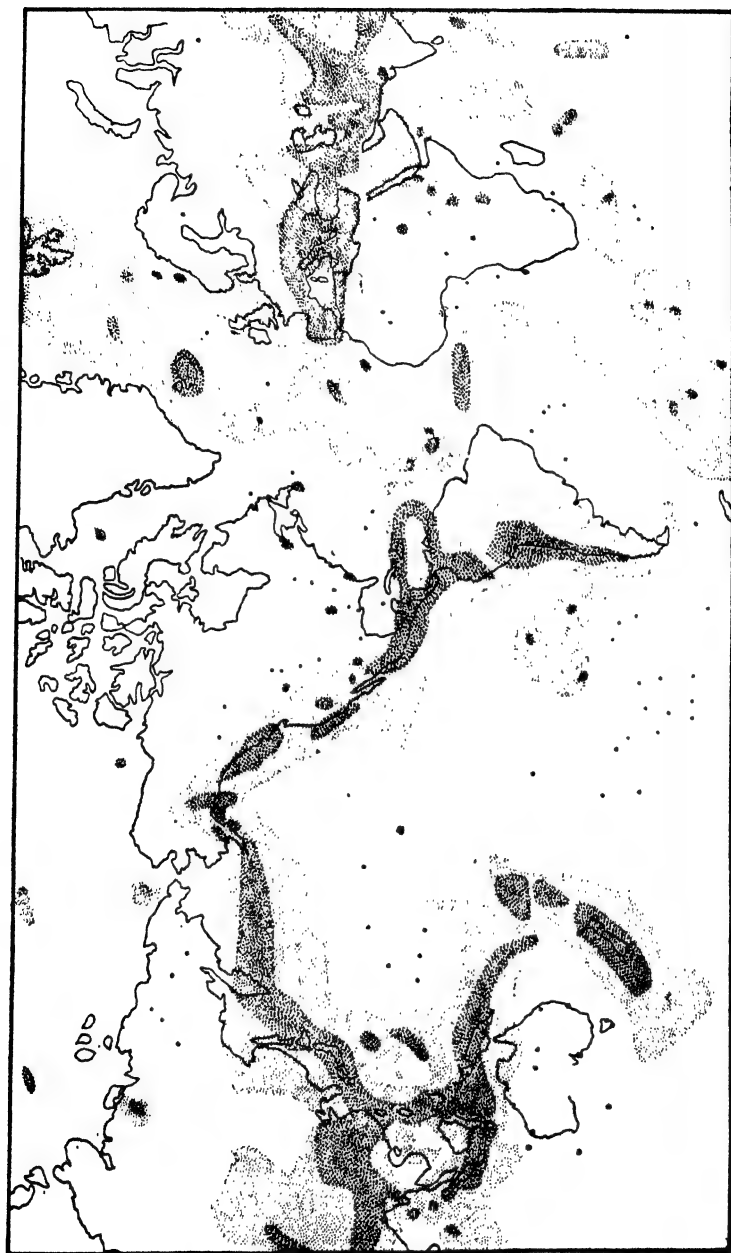



Fig. 187

Maps showing the distribution of the epicentres of recent earthquakes. Heavy shading indicates the occurrence of frequent earthquakes, including most of those of major intensity

of earthquakes originate elsewhere. Expressed in another way, the belts form two rings (*cf.* Figs. 209–10) : one enclosing North America and most of Asia and Europe (known collectively as *Laurasia*), and the other enclosing South America, Africa and Arabia, India, Australia, and Antarctica (known collectively as *Gondwanaland*). From Portugal to Burma the two rings coalesce. These belts or rings are also those of Tertiary and recent mountain building. Judged by the frequency of catastrophic shocks, the most dangerous lands are, in order, the Philippines, Italy, China, Asia Minor, Japan, Mexico, and the Balkans.

In the immediate neighbourhood of active volcanoes tectonic earthquakes are rare, though the latter may be numerous within a hundred miles or so. Earthquakes tend to occur most frequently and severely on the outer sides of mountain and island arcs, especially where the slopes are steep (as off Japan and the Philippines), whereas volcanoes are generally aligned at some distance on the inside of the arcs (see Figs. 211 and 213). In the earthquake belts, steep slopes are direct consequences of geologically recent mountain building, and tectonic earthquakes often originate beneath steep slopes because they result from the present-day continuations of the same movements.

A minor belt of epicentres extends from Spitzbergen and Iceland, along the mid-Atlantic " swell," to Bouvet Island in the far south. Another runs from the Nile through the rift valley region of eastern and central Africa (see page 433), with a side branch from the Gulf of Aden through the Indian Ocean east of the Seychelles. Even in the more stable regions of the continents and ocean floors, sporadic shocks occasionally occur. In 1929, for example, a powerful earthquake originated between Nova Scotia and Newfoundland. No place can be regarded as permanently immune from shocks. Earthquakes are rare in Britain and most of those that do occur can be traced to belated movements along ancient faults such as the Great Glen Fault along the Caledonian Canal and the Highland Border Fault between the Grampians and the Midland Valley of Scotland (see Fig. 180).

Seismographs and Seismic Waves

From the focus of an earthquake, waves are propagated through the earth in all directions, and when they arrive at a seismological station they are recorded on seismographs, provided they are not too vigorous to put the instrument out of action. Fig. 188 shows the essential parts of a common type of horizontal seismograph. The vibrations of the ground are transmitted to a delicately poised, weighted boom which swings horizontally against a massive support which is firmly attached to the ground. The weight tends to remain stationary,

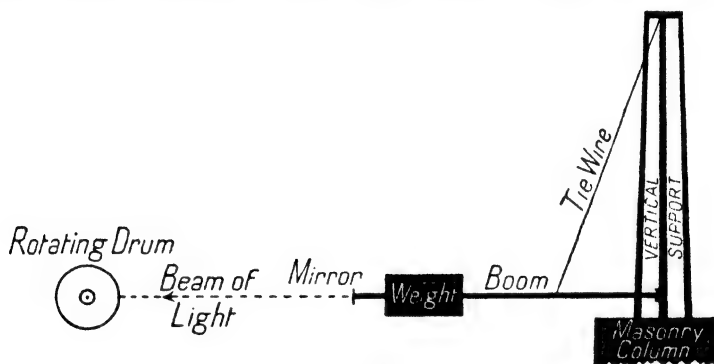



Fig. 188
Diagram to illustrate the essential parts of a horizontal seismograph of the Milne-Shaw type

and the movement of the end of the boom thus reproduces the horizontal components of the vibrations of the support. A small mirror attached to the end reflects a beam of light on to photographic paper wrapped around a drum which rotates on a long screw, so that while rotating it carries the paper along at right angles to the reflected beam of light. The vibrations are thus continuously recorded on the paper with a magnification that depends on the length of the reflected beam of light.

The record of a distant earthquake has the appearance illustrated in Fig. 189. A first or primary pulse P is followed by rapid oscillations ; then comes a second pulse S, followed

by more oscillations ; and finally a third pulse L initiates the " long " or " main " vibrations. The P or " push-and-pull " waves are compressional waves like those of sound, in which each particle vibrates in the direction of propagation. The S or " shake " waves are distortional waves, in which each

Fig. 189

Record at Pulkovo, Russia, of an earthquake in Asia Minor (February 9, 1909). The time interval S-P is 3 minutes 43 seconds, corresponding to a distance of 1,400 miles from the epicentre. (*After B. Galitzin*)

particle vibrates at right angles to the direction of propagation. The velocity of P depends on the density and resistance to compression of the rocks traversed ; that of S on the density and resistance to distortion. The deeper the waves go (until the earth's core is reached), the faster they travel. At each

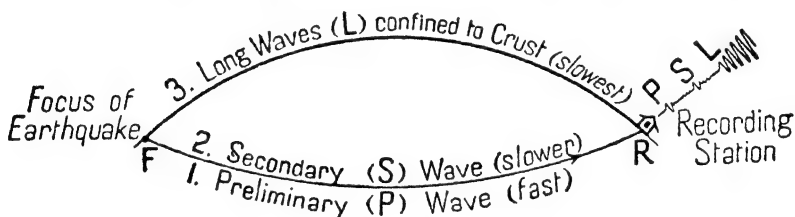



Fig. 190

Section through a segment of the earth showing the paths followed by the P, S, and L waves generated by an earthquake at F and recorded at R

depth, P travels more rapidly than S, and is thus recorded first (Fig. 190). The L waves are those that are confined to the crust by reflections up and down at its lower and upper surfaces ; they follow a zig-zag path, and thus arrive later than the others. Their existence shows that there *is* a crust, and that the crust overlies a substratum with different properties.

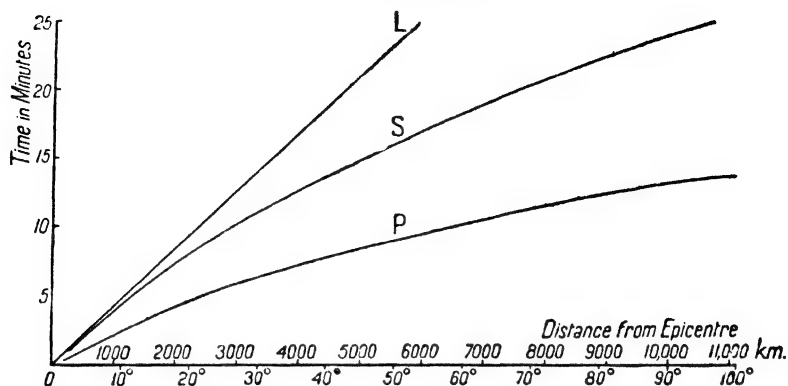



Fig. 191
Time-distance curves for P, S. and L waves

When the times of travel of P and S to various stations are plotted against the corresponding distances from the epicentre, they fall on smooth curves which are the same for all distant earthquakes (Fig. 191). An important feature is that the time

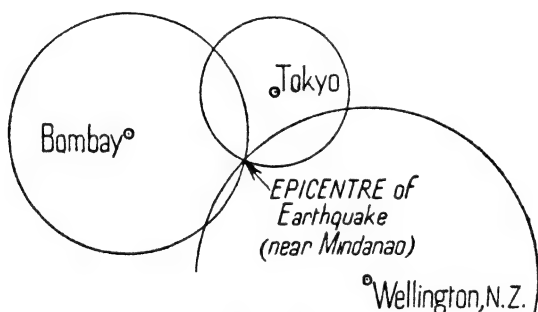



Fig. 192
To illustrate how the epicentre of an earthquake can be fixed when its distances from three suitably placed stations are known. A circle is drawn on a globe around each of the three stations (*e.g.* Bombay, Tokyo, and Wellington), with a radius corresponding in each case to the respective distance of the epicentre. The epicentre lies at the point of intersection of the three circles

interval, S–P, steadily increases with the distance. Thus, when an earthquake is recorded at any station, a measurement of the interval, S–P, determines the distance of the epicentre and

the time of origin. Three distance determinations at three well-spaced stations serve to fix the actual position of the epicentre (Fig. 192).

THE STRUCTURE OF THE EARTH'S CRUST

Seismograph records are of great interest to geologists because they provide the most powerful available means of exploring the earth's interior. The P and S waves of distant earthquakes descend far beneath the crust, but those of near earthquakes (within a few hundred miles of the stations where they are recorded) travel through the crustal rocks with velo-

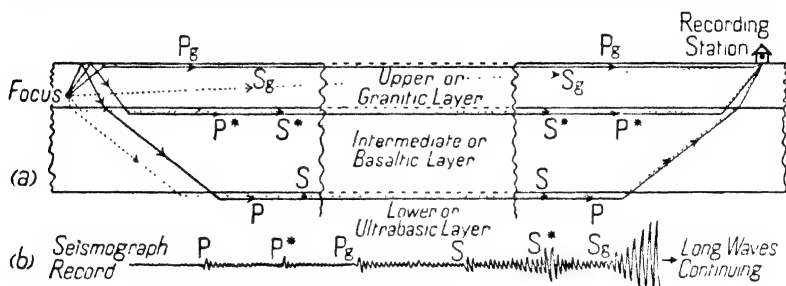



FIG. 193

(*a*) Diagrammatic section through the crystalline layers of the continental crust to show the probable paths followed by the six waves of P and S types observed in the record (*b*) of a near earthquake. (*After H. Jeffreys.*) Waves traversing the upper layer are distinguished as P_g and S_g; those traversing the intermediate layer as P* and S*; and those traversing the lower layer as P and S

cities that are characteristic of the rocks through which they pass. The waves that travel through the *upper layer* of the continental crust generally have velocities of 5·4 (P_g) and 3·3 (S_g) km. per second (Fig. 193). These velocities agree with those calculated from the densities and elastic constants of granitic rocks, and it is therefore inferred that the upper layer of the continents is made of granitic rocks. Waves that have traversed overlying "veneers" of sedimentary rocks, P_s and S_s, have lower velocities, and thus give on the records pulses which follow those of P_g and S_g, and can therefore be distinguished. Other waves dive below the granitic layer before

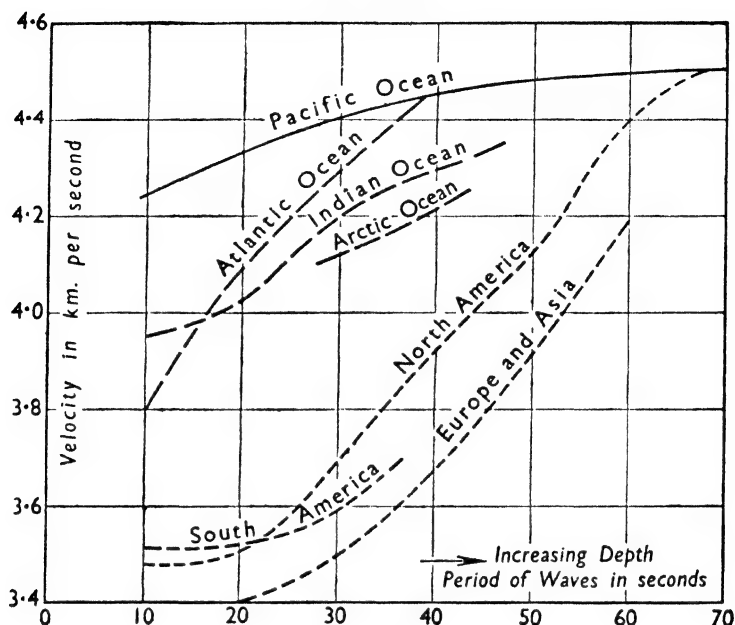



Fig. 194

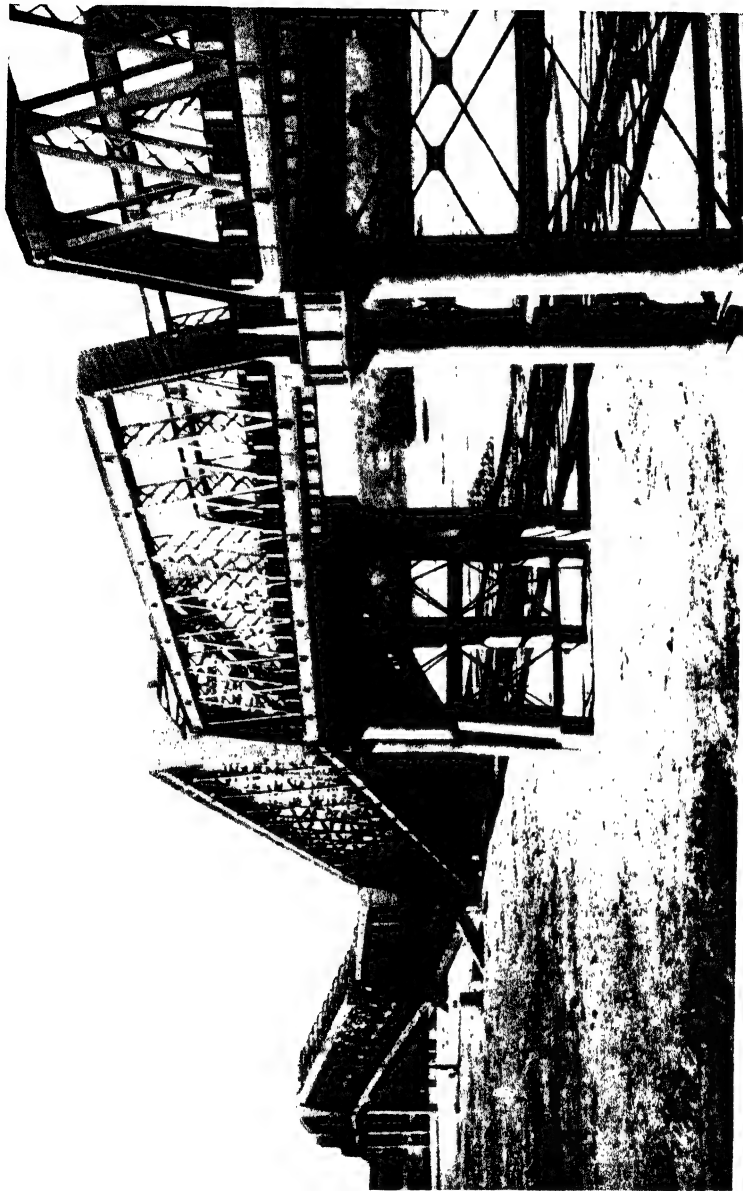
Diagram showing the velocities of long waves of different periods which have traversed the crust of the regions indicated. The longer the period the deeper is the penetration of the wave concerned. The results demonstrate the contrast in structure between the continental crust (with a granitic layer) and the Pacific crust (without a granitic layer), and show that the granitic layer is relatively thin or patchy beneath the other oceans

returning to the surface, and pass through a series of *intermediate layers* with velocities ranging from 6·0–7·2 (P*) and 3·5–4·0 (S*) km. per second. These velocities correspond approximately to those of plutonic and metamorphic rocks having a composition like basalt. Waves that penetrate still deeper, like those of distant earthquakes, pass through the *lower layer* with velocities of 7·8 or more (P) and 4·35 or more (S) km. per second. These correspond to the heavy rock materials of the sima, possibly comparable in composition to peridotite but probably differing in many respects from any known surface rocks.

The thicknesses of the continental layers can be estimated

(A) Gaping fissures in a country road near Yokohama

(B) Buckling of railway lines near Tokyo

JAPANESE EARTHQUAKE OF 1st SEPT. 1923

Breakdown of the Nagara-Gawa railway bridge, Japan. Mino-Owari earthquake, 28th October 1891

E.N.A.

from the travel times of the various waves, the results being as follows :

Sedimentary layer	0–10 km. (widely variable)
Upper or Granitic layer . .	10–15 km. (becoming much thicker under the Alps and the Caucasus)
Intermediate or Basaltic layers	20–30 km. (becoming much thinner under the Alps and the Caucasus, but thicker under the Sierra Nevada (U.S.A.)
Lower layer	Continuing down to the earth's core at a depth of about 2,900 km.

The structure of the oceanic crust is less well known, because there are few island stations at which earthquakes can be efficiently recorded. From the velocities of L waves which have travelled along the oceanic crust before being recorded it appears that the granitic layer is missing from the crust underlying the greater part of the Pacific, and that it is present only in relatively thin patches below the Atlantic and Indian oceans (Fig. 194). Most of the oceanic crust seems to be like that of the deeper parts of the basaltic layers beneath the continents. At greater depths the materials have the same properties beneath both oceans and continents.

The Structure of the Deep Interior

The P and S waves of distant earthquakes reach great depths and their travel times indicate that their velocities increase with depth from the figures given above to about 13 (P) and 7 (S) km. per second at a depth of 2,900 km. Relatively rapid changes occur at about 400 and 700 km., but whether these correspond to changes of composition or of state (*e.g.* from crystalline to glassy) is not yet known. However, at 2,900 km. there is a most conspicuous change (Fig. 195). The waves that just attain this depth emerge at the surface at places about 11,000 km. from the epicentre of the earthquake concerned. Stations lying up to 5,000 km. beyond this distance record no P or S waves, though the L waves come along as usual. At distances more than 16,000 km. from the epicentre of the earthquake the P wave again appears and it continues

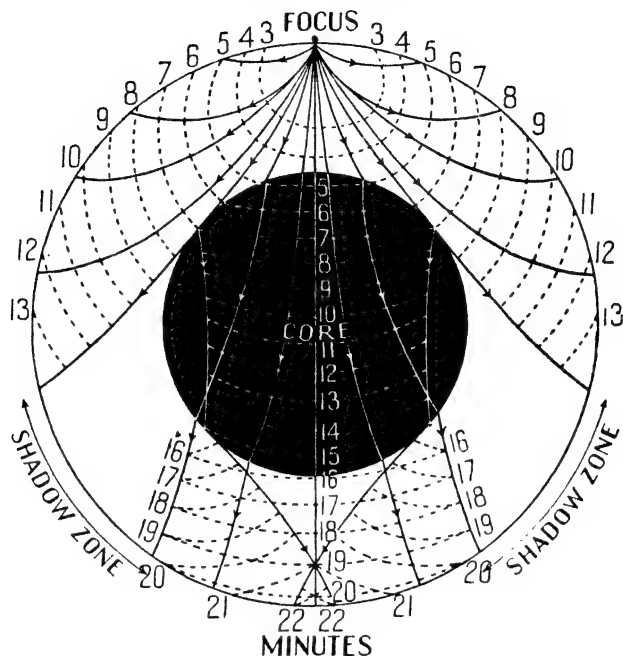



FIG. 195

Section through the centre of the earth showing the wave paths (firm lines with arrows), wave fronts (dotted lines), and arrival times (in minutes reckoned from the zero time of the shock). Since there is a shadow zone free from P and S waves for each such earthquake, it is inferred that the earth has a core which refracts the deeper waves as shown in the diagram

to do so right up to the antipodes of the epicentre. Corresponding to each earthquake there is thus a ring-like shadow, free from P and S waves, as illustrated in Fig. 196. The part of the earth which casts this shadow is called its *core.*

P waves pass through the core with a greatly reduced velocity, but S waves are not transmitted at all. Since it is characteristic of liquids that they have no distortional elasticity, and that S waves cannot pass through them, it is inferred that the earth's core is essentially liquid. The material itself is thought to be mainly iron with a small percentage of nickel, partly because such a composition matches the high density of the earth and the velocity of the P waves through the core ;

FIG. 196
The shadow zone cast by the earth's core in the case of an earthquake originating in Japan

partly because it corresponds with the composition of iron meteorites, which are probably samples from the interior of a disrupted planetary body ; and partly because the presence of abundant iron oxides in the crustal rocks implies a high concentration of iron in the interior, just as in a blast furnace a little oxidised iron remains in the slag, while most of the iron sinks to the bottom.

SUGGESTIONS FOR FURTHER READING

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Chapter XVIII

EARTH MOVEMENTS: MOUNTAIN BUILDING

The Nature of Orogenic Belts

As already indicated on p. 106, an orogenic belt is an elongated structural zone of the earth's crust in which the rocks have been folded, crumpled, contorted or overthrust on a spectacular scale. As a consequence of the thickening of the crust due to intense lateral compression, long sections of each orogenic belt are uplifted, thereby becoming mountain ranges, like the Alps and the Himalayas, with a varied relief of high peaks and deep valleys carved by the agents of denudation. Most of the great mountain ranges of to-day are parts of orogenic belts that came into existence at various times of crustal unrest since the Jurassic period, and particularly during the Tertiary period. Others, like the Appalachians and the mountains of Scandinavia and Britain, represent older orogenic belts that were deeply eroded long ago, but have since been rejuvenated, so to speak, by uplift associated with the crustal compression of Tertiary times.

While all the present-day ranges of folded mountains represent uplifted orogenic belts, it must be clearly realised that by no means all orogenic belts are now mountainous. Most of the Pre-Cambrian orogenic belts and certain stretches of the later ones have lost their original mountainous relief by long continued denudation, so that the rocks now exposed to view (*e.g.* along the mainland and island shores of southern Finland (Plates 10 and 11) are those which were formed by metamorphism and igneous activity far below the surface at the time when the region was undergoing active deformation. Some sections of orogenic belts are submerged below sea level. Between Scandinavia and Britain, for example, the Caledonian orogenic belt lies beneath the North Sea. The Black Sea, which has only recently been formed by subsidence, hides the

submerged connecting links between the Caucasus and the Crimea and the Balkan Mountains. It is therefore essential to discriminate carefully between the geographical concept of a mountain range or system and the geological concept of an orogenic belt : the one refers to the height and relief of the land ; the other to the structure of the rocks, whether the region be high, low, or submerged. A mountain system is the whole series of ranges belonging to an orogenic belt. The term *cordillera* is sometimes used for a broad assemblage of ranges—such as that of western North America—belonging to more than one system (see Figs. 201 and 219).

We have already learned that mountainous orogenic belts have deep sialic roots which go down to depths comparable with the whole thickness of the crust. It follows that the compression responsible for the development of an orogenic belt disturbs all the rocks down to a very great depth. In all the greater crustal revolutions the previous structures of the rocks are entirely altered : by folding and thrusting in the upper levels, and by flowage and metamorphism below, culminating in fusion and igneous activity. Indeed, it is only in the orogenic belts that the complete cycle of rock transformation (page 66) is achieved on a regional scale. Changes of chemical composition—as in the transformation of sediments to schists and migmatites, and even to granites—are brought about by hot migrating fluids. Magmas are generated in the crust ; others ascend from greater depths ; and valuable deposits of metallic ores are locally introduced. Orogenesis thus involves not only great lateral compression, but also the heating of the rocks and the soaking through them of chemically active fluids. The tectonic, thermal, chemical, and magmatic changes that accompany the great crustal revolutions are thus in striking contrast with the relative passivity of the wide intervening regions where the dominant movements are epeirogenic (p. 107). In these areas only slow fluctuations of level take place, accompanied by fracturing and faulting. Folding, if it occurs at all, is local and on a limited scale.

Geosynclines

By the work of several generations of geologists it has been firmly established that the orogenic belts of each geological era originated in long downwarps of the crust in which extraordinarily thick deposits of sedimentary rocks accumulated during the era (or eras) that preceded the orogenic revolution. The first important step towards understanding the natural history of folded mountains was taken nearly a century ago

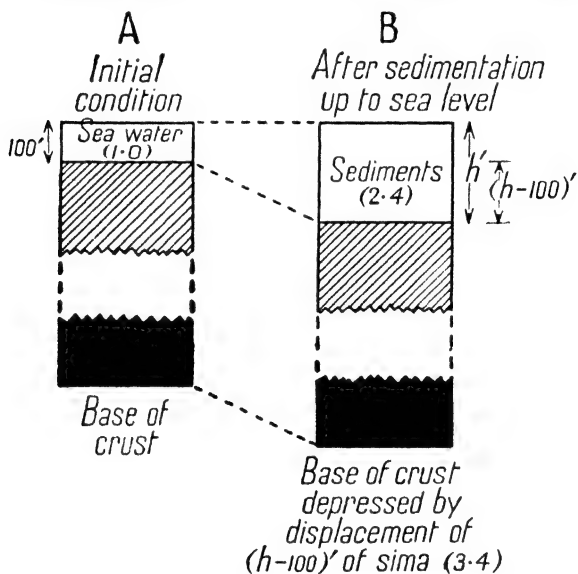



Fig. 197
Diagram to illustrate the isostatic response of the earth's crust to sedimentation

by the brothers W. B. and H. D. Rogers. From their study of the Appalachians these two geologists discovered that the folded sediments out of which the ranges are built are shallow water marine types which locally reach a thickness of 40,000 feet. In the unfolded regions of the Interior Lowlands to the west the sediments of corresponding age are only a tenth or a twentieth as thick.

The accumulation of several miles of sandstones, shales,

and limestones clearly implies that the original floor of the belt must have subsided by a like amount. The mountains were evidently preceded by the gradual development of a deep trough in which sedimentation more or less kept pace with the downwarping of the crust. Such elongated belts of long continued subsidence and sedimentation were called *geosynclines* by Dana in 1873.

The early pioneers thought that the weight of the accumulating sediments was itself sufficient to depress the crust, so that room was automatically provided for still more sediments. Any such effect, however, is strictly limited. Suppose the initial depth of sea water to be 100 feet (stage A in Fig. 197) and that marine sediments of density 2·4 accumulated, and depressed the crust isostatically, until the region became completely silted up (stage B). Let the maximum thickness of sediments so deposited be h feet. The crust is depressed by $(h - 100)$ feet, and this must also be the thickness of the deep-seated sima, density 3·4, displaced at the base of the crust. At stage B

the weight of sediment added is proportional to $2{\cdot}4 \times h$
the weight of water displaced is proportional to $1{\cdot}0 \times 100$
the weight of sima displaced is proportional to $3{\cdot}4 \times (h - 100)$.

For isostasy to be maintained the weight lost must be equal to the weight gained. Thus, we have

$$2{\cdot}4\ h = 100 + 3{\cdot}4\ h - 340\ ;\ \text{whence}\ h = 240\ \text{feet.}$$

For 40,000 feet of marine sediments to accumulate under such conditions, the initial depth of water would have had to be nearly 17,000 feet. Actually, however, the water was very shallow to begin with, as shown by the abundance of shore and deltaic deposits. It follows that the weight of sediments does not depress the crust to any significant extent. It is the independent downwarping of the crust that makes room for the sediments to accumulate. A geosyncline is essentially a result of earth movements, the precursors of the vigorous revolutionary movements that follow at a later date. It may be noticed in passing that the average rate of sinking is ex-

tremely slow. In the Appalachian example, 40,000 feet in 300,000,000 years (Cambrian to early Permian) is only one foot in 7,500 years. However, this very slowness makes the cumulative effect seem even more remarkable.

The continual supply of sediments implies that the land bordering at least one of the shores of a geosyncline must have been rising while the floor of the geosyncline was sinking. Near the shore, or wherever the curvature of the warped crust is greatest, fractures and faults may develop. Volcanic activity, evidenced by the occurrence of lavas and tuffs, interbedded with the sediments of many geosynclines, would be expected to take advantage of such fractures through the crust. In Britain vulcanism broke out on a large scale during the Ordovician period, while the Caledonian geosyncline was developing (Figs. 51 and 200). Volcanic rocks first appeared at Rhobell Fawr in Wales and on both sides of the Midland Valley of Scotland (Fig. 180). Later, the activity spread towards the middle of the geosyncline and brought to the surface the lavas and tuffs which are responsible for the rugged scenery of Snowdonia in North Wales (Plate 54B), and of Borrowdale (Plate 37) in the Lake District. Such volcanic activity indicates that the rocks beneath the geosyncline were being heated up as well as depressed.

Structures of Orogenic Belts and their Implications

Some of the structures characteristically impressed by subsequent compression upon the vast thicknesses of sediments (and of volcanic rocks, when present) have already been illustrated. These structures include alternations of more or less open anticlines and synclines (Plates 12 and 80) ; tightly compressed isoclinal folds (Fig. 26 and Plate 69A) ; recumbent folds (Fig. 27 and Plate 81) ; and thrusts and nappes (Fig. 33). A folded mountain range is a linear tectonic unit, straight or arcuate, in which the axes of the folds are generally parallel to the main trend of the range. The axial planes, recumbent folds, and thrusts are all (except for parts of an occasional

anticlinorium or synclinorium, Fig. 26) directed upwards and outwards from the interior of the geosyncline towards one of the unfolded crustal blocks which margined the geosyncline. The crustal block towards or over which the structures splay

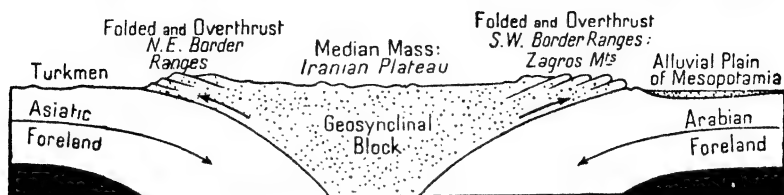



FIG. 198

Hypothetical section across the symmetrical orogenic belt of Iraq and Iran, indicating the approach of the forelands and the outward thrusting of the margins of the geosynclinal block (folding of the marginal ranges omitted)

out is called the *foreland*. Most geosynclines have two forelands, but where a geosyncline developed alongside a continental margin (as in the Dutch East Indies) the outer foreland is the ocean floor beyond the zone of depression. The resulting mountain system is thus characteristically bilateral, and consists of two unilateral bordering ranges (or series of ranges), each having its structures directed outwards, away from the axis of the geosyncline. Each bordering range, taken by itself,

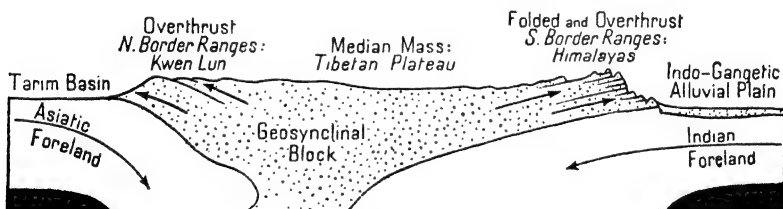



FIG. 199

Hypothetical section across the asymmetrical orogenic belt of the Himalayas and Tibet (folding of the marginal ranges omitted)

is a unilateral range, in which all the structures splay out the same way, that is, towards the neighbouring foreland.

This unity of structure is particularly well displayed by the Alpine system of ranges (Figs. 198 and 199). The Alpine-Himalayan system as a whole extends from each side of

Gibraltar on the west, to the Himalayas and the East Indies on the east. It originated in a long, wide, and composite geosyncline which developed between the northern foreland of Europe and Asia (Eurasia) and the southern foreland of Africa, Arabia, and India. To distinguish this immense seaway from the present Mediterranean it was called the *Tethys* by Suess. By subsequent compression two main sets of ranges originated : a northerly set, including the Pyrenees, the Alps, the Carpathians, and the Caucasus ; and a southerly set, including the Atlas Mountains, the Apennines, the Dinaric Alps, the Tauric ranges, and the Himalayas. Where these bordering ranges lie far apart there may be a broad intervening region of sea, plain, or plateau. Examples of these are the Western Mediterranean, the Hungarian plain, and the high plateau of Tibet. Such intermontane, relatively unfolded regions are called *median* areas. Where there is no median area and the bordering ranges are closely compressed together, back to back, the bilateral structure may be roughly symmetrical, but it is generally conspicuously asymmetrical. The Western Alps, for example, are so highly asymmetrical as to be almost unilateral, all the thrusts and recumbent folds, except in the extreme south, being directed towards the European foreland (Fig. 204).

The direction of overfolding and thrusting, and of the crustal compression responsible for the over-riding movements, is naturally described as it is seen at the surface ; that is to say, with reference to the underlying rocks, which are implicitly regarded as having remained stationary. Thus the overthrusts of the North-West Highlands (Fig. 33) or the nappes of the Western Alps (Fig. 204) are said to be directed towards the north-west as a result of pressure from the south-east. But this description is purely relative. Exactly the same effect would be attained if the foreland rocks had been underthrust towards the orogenic belt. Now in bilateral systems we observe that on each side the overthrusting and the corresponding pressure appear to have come from within the system. Pressure could not, however, have operated outwards in two diametrically opposed directions unless the deeper levels of the geosynclinal belt had been powerfully compressed from

outside, that is, by the inward movement of the two forelands. The crustal blocks of the forelands have, in fact, acted like the jaws of an irresistibly closing vice, underthrusting the geosyncline, and so causing its sediments and floor to crumple up and splay out on both sides. The crustal shortening involved in the folding and thrusting can often be roughly estimated by imagining the structures to be all straightened out ; it commonly amounts to many tens of miles. As the forelands move inwards, the rocks in depth, already downwarped during the growth of the geosyncline, continue to buckle downwards (Fig. 212) with consequent formation of a deep mountain root. Only the upper strata of the geosyncline itself tend to wrinkle upwards. The general uplift of the region into a belt of highlands follows later, as a result of isostasy (page 15).

Orogenic Belts of Europe

The general outlines of the tectonic framework of Europe are shown in Fig. 200. The oldest part of the continent is the Baltic Shield. This broad region of geologically ancient crystalline rocks has remained a stable land area ever since pre-Cambrian times. It has fluctuated in level from time to time, but on the whole the movements have been slow gentle uplifts which maintained the surface above sea level, despite the ravages of denudation. Towards the east and south, however, the old rocks of the Shield are covered by a veneer of flat-lying sediments, deposited during the Palæozoic and later periods. This buried extension of the Shield, known as the Russian Platform, evidently subsided a little at intervals and was flooded by shallow seas, just as part of the Shield is flooded to-day by the Baltic. North of the Black Sea, and in a few other isolated spots where the sedimentary blanket has been removed, the shield rocks reappear at the surface. The north German plains and probably the English Midlands represent a westerly continuation of the Russian Platform, although in this section the crust was less stable, and certain basins of sedimentation that were deeper than usual—including most

FIG. 200

Tectonic map of Europe. The Alpine orogenic belt is outlined by thick black lines with arrows indicating the outward thrusts and overfolding towards the forelands

of the great coalfields of Britain—have suffered a certain amount of folding.

The stable triangle of the Shield and Platform is bordered on its three sides by clearly defined orogenic belts, towards each of which it acted as a rigid foreland. On the north-west the Caledonian belt extends through Scandinavia to Britain. Here the rocks of a Lower Palæozoic geosyncline were intensely folded, overthrust, and invaded by granites during late Silurian and early Devonian times. In Scandinavia the south-eastern front of the belt is well preserved. Outward thrusting towards the Shield is conspicuous in many places and has involved movement of possibly as much as 80 miles. Within the belt itself the rocks are contorted, metamorphosed, and granitized

so intensely that over large tracts the structures baffle analysis. The north-western front of the belt is cut off by the Atlantic, except in the N.W. Highlands of Scotland, where the thrusts illustrated in Fig. 33 splay out over another shield area, of which only a narrow strip now remains as land. This relic of the north-west foreland probably represents the extreme limit of the great Canadian Shield of North America and Greenland (Fig. 201). The south-eastern front of the Caledonian belt is poorly defined in Britain. Much of it is hidden by later sediments, and where the older rocks are exposed—as in Shropshire—the folding is open and broadly undulating.

While the Caledonian movements were in progress, other geosynclines began to develop and to fill up with sediment : (*a*) along the site of the Urals ; and (*b*) across Central and Southern Europe from the promontories of south-west Ireland to north of the Sea of Azov. These became transformed into orogenic belts during Carboniferous and early Permian times. This orogenesis and the structures and mountains that resulted are known by the name *Hercynian* (after the Harz Mountains). Most of the Uralian belt is continuously preserved, but the much wider Hercynian belt of the south has become broken into a series of isolated blocks or *massifs*. These include south-west Ireland, South Wales, and Cornwall and Devon ; Brittany and the Central Plateau of France ; the Ardennes, Vosges, and Black Forest (Plate 82A) ; and the Harz and Bohemian Mountains. The depressed regions between are buried beneath later sediments, but here and there (*e.g.* in south-east England) the Hercynian foundation has been encountered in borings and mining operations. There is no doubt that all the massifs referred to are relatively uplifted parts of a belt that is continuous in depth.

The southern margin, and locally the whole, of the Hercynian belt has vanished from sight for another reason. In Mesozoic times considerable stretches of the Hercynian tract became submerged beneath the Tethys, so forming the greater part of the floor of the Alpine geosyncline. Other portions, such as the massifs of Mt. Blanc and the Aiguilles Rouges, remained as islands near the northern shores of the Tethys

(Plate 82B). These, together with parts of the floor itself, were incorporated in the Alpine ranges which later completed the southern framework of Europe.

In most places the northern Hercynian front lies well to the north of the northern Alpine front, but the Carpathians were thrust forward beyond the Hercynian front, so that here the Russian Platform became the foreland. In Silesia the structural relations between the mountains and their foreland have been made clear by mining operations. The broad coalfield of Silesia—belonging to the foreland—was partly overridden by the advancing nappes of the Carpathian arc. Nevertheless, the buried half of the coalfield has been located beneath the nappes by borings sunk through them into the coal seams beneath.

Just as the Alpine structures encroach on the older Hercynian belt, so in the British Isles (see Fig. 258) the Hercynian structures in turn encroach on the still older Caledonian belt. From South Wales to the south-west shores of Ireland the Lower Palæozoic rocks with their typical Caledonian structures disappear beneath the folded and overthrust Devonian and Carboniferous sediments which represent the northern Hercynian front. The two orogenic belts, gradually converging across Europe, ultimately meet, and the northern Hercynian front begins to cross the south-eastern Caledonian front. What is probably the completion of the crossing is found in the Appalachian Mountains on the other side of the Atlantic.

The Appalachians

These mountains (Fig. 201) appear to be a closely knit complex of two systems which roughly correspond to the Caledonian and Hercynian of Europe, though in each case the main orogenesis was slightly later in age. Originally, the Appalachians were regarded as the standard example of a unilateral mountain system, with the structures all directed towards the Canadian Shield (a stable region of the same type as the Baltic Shield) and its buried continuation beneath the

Fig. 201
Tectonic map of North America

Interior Lowlands (a region corresponding to the Russian Platform). This apparent simplicity, however, only reflects the fact that along the Atlantic seaboard the south-eastern side of the orogenic belt is everywhere concealed by the later sediments of the Coastal Plain (Fig. 202). The foreland on the south-east is not seen, because the Atlantic now occupies the site where we should naturally look for it. But that there certainly was such a foreland is firmly established by the observation that the geosynclinal sediments become coarser as they are traced towards the Atlantic and include deltaic deposits which spread out towards the north-west. Clearly the rivers that supplied these sediments must have drained a

land that lay to the south-east, a land that must have been undergoing denudation throughout the greater part of Palæozoic time.

In the north the overthrust Appalachian front begins in Newfoundland. Continuing along the line of the St. Lawrence as far as Quebec, it then turns south towards New York. During the Devonian all this northern section was folded, overthrust, invaded by granite, and uplifted by an orogenesis that corresponds with the later phases of the Caledonian revolution. South-west of New York the Caledonian part of the chain is probably represented by the "Older Appalachians" (Fig. 202), where the old basement rocks, representing the floor of the geosyncline, intensely deformed and penetrated by granite, were overthrust towards the north-west. In this region only a few infolded and highly metamorphosed

FIG. 202

Section across the composite orogenic belt of the southern Appalachians

remnants of the geosynclinal sediments now remain. We see deep into the heart of the former mountains.

Inland, however, between the Blue Ridge and the Appalachian Plateau, the sediments are largely preserved in a broad series of deep folds. These are generally open, as shown in Fig. 202, but in places, *e.g.* the slate regions of West Virginia, the folding is isoclinal and is locally broken by thrusts, again indicating movement towards the north-west. Still farther inland, in the Plateau, the folding gradually flattens out. In these "Newer Appalachians" not only Lower Palæozoic sediments are found, but also a far thicker sequence belonging to the Upper Palæozoic. The whole assemblage was folded during the main Appalachian revolution, which began in the Carboniferous and reached its climax in the Permian. The "Newer Appalachians" thus correspond with the later phases of the Hercynian orogenesis. By measuring the folds it has

been estimated that the folded " ridge and valley " tract, now about 65 miles across, had an original width of about 100 miles. The forelands thus approached by at least 35 miles. Many batholiths and stocks were emplaced in the heart of the growing range, particularly in the adjoining " Older Appalachians " which must therefore have shared in the later orogenesis.

Farther north, in the New England States, relics of strongly folded Carboniferous rocks mark the continuation of the " Newer Appalachians." But here they lie on the inner side of the Caledonian front of the Appalachian system, whereas in the south the folded belt is on the outer side. The " Newer " or Hercynian front appears on the coast near Boston, reaches the " Older " or Caledonian front behind New York, and then, as Bailey puts it, " steps clear of its Caledonian predecessor." The crossing of the Caledonian belt by the outer front of the Hercynian belt, begun in Britain, is finally accomplished in America (Figs. 201 and 258).

The Western Alps

The folded structures of the Appalachians are simple and straightforward compared with the amazing complexity of the recumbent folds and far-driven nappes of many of the Alpine ranges. Since Escher's discovery in 1841 of gigantic thrusts in the Swiss Alps, many brilliant geologists have devoted their professional lives to the unravelling of structures which, for many years after they were first described, appeared to be quite incredible to those who had not actually traced them from peak to peak. By patient mapping, supplemented by underground observations made possible by an incomparable series of tunnels, the intricate tectonic pattern of the Swiss Alps is now known with a wealth of detail superior to anything that has been achieved in the other great mountain systems of the world.

Geologically the Alps are divided into the *Western Alps*, which curve in a broad arc from the Mediterranean to Lakes

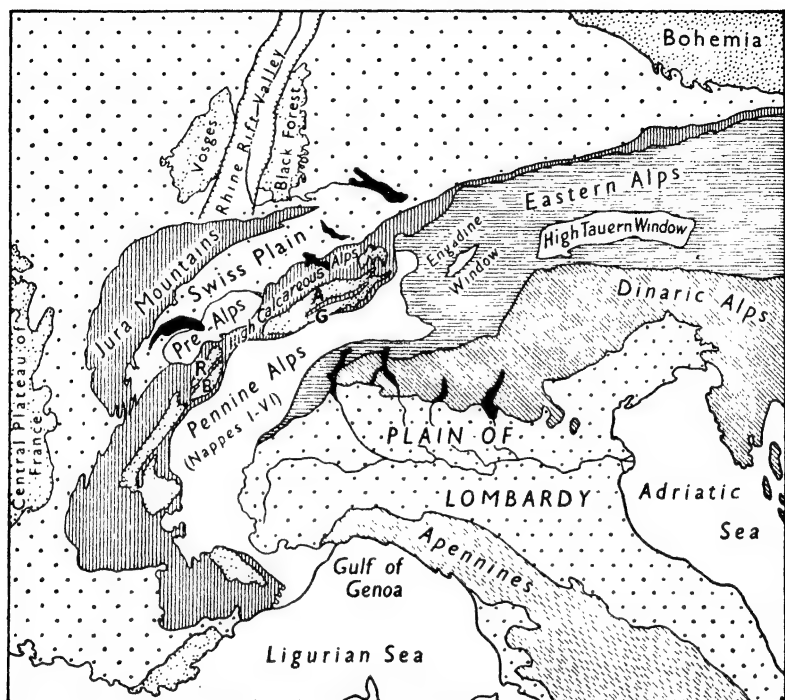



FIG. 203

Tectonic map of the Alps. Hercynian massifs are indicated by close dotting (A=Aar Massif; G=St. Gotthard Massif; R=Aiguilles Rouges; B=Mt. Blanc)

Constance and Como, and the *Eastern Alps*, which continue in a gentler curve towards the Danube (Fig. 203). Beyond Vienna the vast bow of the Carpathians begins, while on the southern side the ranges of northern Italy swing round into the Dinaric Alps. It is in the Western Alps, and particularly in Switzerland, that the key to the general structure has been revealed. The essential feature, as portrayed in Fig. 204, is the occurrence of a series of gigantic recumbent folds and nappes, each of which has been driven forward for many miles towards the foreland, and in many cases far across it. The Alpine rivers have cut deeply into the nappes, thus exposing the underlying rocks in many a steep-walled valley. If the nappes were everywhere at the same level, only the

outer parts of the structure would be exposed to view in this way, and even the tunnels would add little more. But as the nappes are traced along the trend of the ranges from S.W. to N.E. they are found to undulate up and down in an alternating

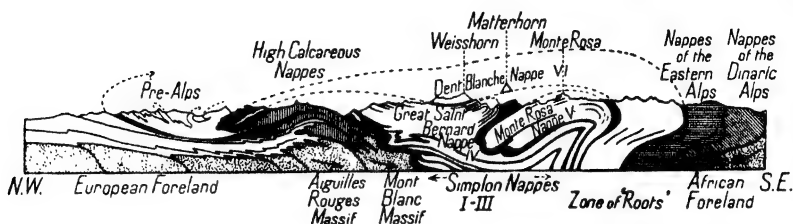



FIG. 204

Tectonic section across the Western Alps (*After R. Staub*)

succession of broad *culminations* and *depressions* (Fig. 205). Where the depressions carry the nappes downwards, the uppermost ones are still well preserved in the mountain peaks. Where the culminations raised the upper nappes to levels now far above the highest peaks—that is to say, where they have already been swept away by erosion—the lower nappes come

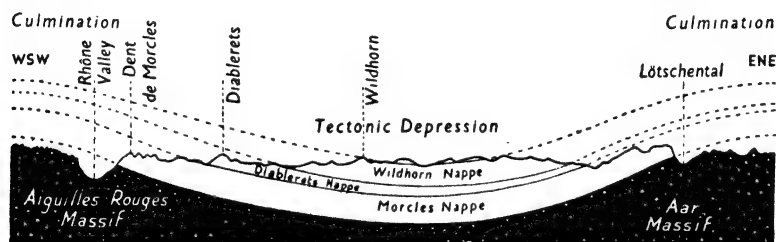



FIG. 205

Longitudinal section showing the nappes of the High Calcareous Alps exposed in the tectonic depression between the culminations of the Aiguilles Rouges and the Aar Massif. The nappes advanced at right angles to the section in the direction away from the observer

to the surface and are themselves cut through by the valleys. Thus, although no single section across the mountains provides more than part of the picture, the whole complicated structure can be visualized by taking a series of several sections in order across the successive culminations and depressions. Finally,

[Peter Christ

Anticline in the Jura Mountains, Moutier Gorge, Switzerland

[F. N. Ashcroft

Recumbent folds in the High Calcareous Alps. The Axenstrasse, near Fluelen, south end of Lake Lucerne, Switzerland

in the Eastern Alps, all the structures seen in the Western Alps disappear beneath a widespread cover of a still higher series of nappes. Thus, because the evidence is largely hidden, the structure of the Eastern Alps is much less well known. Only here and there, as in the Engadine and the High Tauern (Fig. 203) has erosion removed the cover and so opened "windows" in the surrounding framework through which the underlying structures are locally seen.

The chief subdivisions of the Western Alps as seen in plan, subdivisions representing successive zones which provide a first clue to the general structure, can be clearly detected from the air. Each has its distinctive topography, and each comes into view in turn from north-west to south-east during a flight from, say, the Jura Mountains to Milan. In order, these zones are as follows :

1. *The Jura Mountains* : an arcuate bundle of hills, like a crumpled-up tablecloth, pushed forward (while the Alps were advancing) across the gap between the Central Plateau of France on one side and the Vosges and Black Forest on the other, and thus standing well in front of the Alps proper. On the inner side the strata are mainly folded into bold, open anticlines, some of which form the actual hills (Plate 80), but the outer side is a tableland broken by faults into an irregular mosaic of strips and blocks.

2. *The Swiss Plain* : a broad lowland, filled with soft Tertiary sediments called *molasse*, derived from the denudation of the rising Alps. Far to the south-east the edge of the High Calcareous Alps appears in the distance like a great wall (Fig. 206). On each side of Lake Geneva a broad patch of foothills protrudes on to the plain. These are—

3. *The Pre-Alps* : extending between Lake Thun and the River Arve. They consist of an isolated pile of nappes, much folded and sliced by minor thrusts, which were driven over the molasse far from their roots in the south-east. The strata include types which are entirely different from anything seen in the Jura or the High Calcareous Alps. The Pre-Alps are thus completely foreign to the district where they came to

[P. Hauser

FIG. 206
The Swiss Plain and the High Calcareous Alps viewed from the Jura Mountains near Solothurn

rest. Exactly where they came from remains the chief unsolved problem of Alpine tectonics. The uppermost of these far-travelled rock sheets may even represent the remnants of a series of nappes that formerly covered the Western Alps in continuation of the upper nappes of the Eastern Alps. It is possible that the later part of the forward journey of the Pre-Alps was accomplished by down-sliding—like a gigantic landslip.

4. *The High Calcareous Alps* : a high range of rugged mountains whose structure is dominated by a series of clean-cut overthrusts (Fig. 204). The zone includes the Bernese Oberland with its snowfields and glaciers and its many familiar peaks (*e.g.* the Jungfrau, 13,669 ft.). Each of the nappes is composed of sediments which were deposited along the northern margin of the geosyncline. Locally, many of the nappes are themselves intensely folded (Plate 81).

5. *The Hercynian Massifs* : an arcuate chain of long isolated blocks consisting largely of crystalline rocks. These have been sheared by innumerable small thrusts, and except for the more massive granites they fall a ready prey to the splintering action of frost (Plate 82B). The skylines are in consequence characteristically jagged, as in the appropriately named Aiguilles Rouges. The latter massif, together with the adjoining massif of Mt. Blanc (15,732 ft.), emerges along the crest of a great culmination. To the north-east the Hercynian foundation disappears beneath the nappes of the High Calcareous Alps, to emerge again in another culmination as the Aar and St. Gotthard massifs (Figs. 203 and 205). Here the Rhine and the Rhône have their sources. The Rhône flows to the west-south-west through a long trough-like valley which, after leaving the Hercynian massifs, follows the boundary between the High Calcareous Alps and the broad zone of the Pennine Alps.

6. *The Pennine Nappes* : an involved series of six great nappes, all of which were squeezed out of the main geosyncline as gigantic recumbent folds. Each nappe has a core of older rocks, mainly gneisses, representing the floor of the geosyncline ; wrapped round by an envelope of lustrous schists and crystalline limestones, representing the sediments (and volcanic rocks) of the geosyncline. The Pennine Alps (from which our own modest Pennines take their name) is a lofty region of boldly carved mountains, rising above the snowfields into pyramidal peaks, of which the Matterhorn (14,705 ft.) is the most famous (Plate 50), although the less shapely Monte Rosa (15,215 ft.) is higher. To the east the Pennine nappes continue at a lower level as the Lepontine Alps. Beyond the margin of the Eastern Alps they remain unexposed except in the windows of the Lower Engadine and the High Tauern, where the two upper members of the series have been recognized. As numbered in Fig. 204 from bottom to top, the Pennine nappes are as follows :

I–III *The Simplon Nappes* (comprising the three lower nappes), which were pressed against the upstanding mass

of Mt. Blanc and the Aiguilles Rouges and thereby folded into such intricate convolutions that their structure was never made clear until they were penetrated by the Simplon tunnel.

IV *The Great St. Bernard Nappe*, which rides over the Simplon nappes and also sends out a remarkable backward bulge in response to the pressure exerted by the Monte Rosa nappe.

V *The Monte Rosa Nappe*, which, struggling to expand within a writhing complex of plastic rocks, all competing for space, found it easier to plunge into the back of the St. Bernard Nappe than to ride over it.

VI *The Dent Blanche Nappe*, which drove far forward over all the nappes in front, forming above them a widespread carapace, of which the greater part has since been removed by erosion.

7. *The Zone of Roots* : a long narrow zone near the Italian frontier, where the Pennine nappes turn vertically down, and so appear to be rooted in the ground. Some idea of the titanic compression which was involved in the making of the

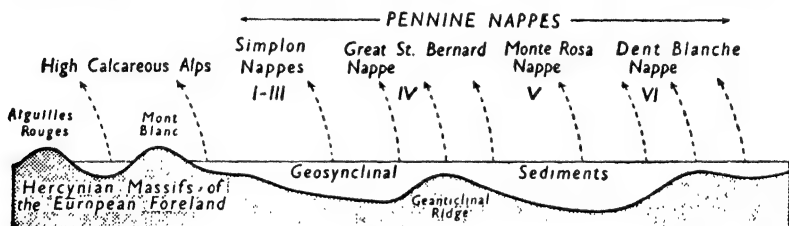



Fig. 207

Reconstruction (in section from N.W. to S.E.) of a stage in the development of the Tethys geosyncline and its northern shores, to illustrate the environments from which the nappes of the Western Alps were driven

Alps can be gained by contrasting this tightly squeezed belt with the great width of the geosyncline that is implied by the sedimentary strata of the nappes (Fig. 207). While the great squeeze was in progress, culminating in Miocene times, the rocks must have been unusually plastic, and evidence that they

were lubricated by hot migrating fluids is furnished by the prevalence of migmatites, with swirling structures due to flowage, in the deepest parts of the roots. Later on, great masses of granite were emplaced at various places along the zone of roots (Plate 83).

8. To the south and west of our line of section the Pennine Alps drop steeply to the alluvial plain of Lombardy. On the east, however, the zone of roots gradually widens with the incoming of still another series of structural elements. These represent the southern side and foreland of the geosyncline, and this time all the thrusts are directed towards the south. From the obscurity of this highly metamorphosed complex the upper nappes of the Eastern Alps emerge, and ultimately turn over to the north, in similar fashion to the Dent Blanche Nappe. Farther south the backward thrusts maintain their direction and mark the beginning of the Italian ranges which pass round the head of the Adriatic into the Dinaric Alps.

The probable relationships between the nappes of the Western Alps and the geography of the obliterated geosyncline are indicated in Fig. 207.

Orogenic Belts of the Alpine Revolution

For convenience the term *Alpine Revolution* is adopted to cover the cumulative effect of all the orogenic movements which have occurred at intervals since late Jurassic times. As indicated by the following examples (which are far from complete), the resulting orogenic belts are not all of the same age.

Late Jurassic (*Nevadan orogeny*) : Atlas, Caucasus, Sierra Nevada of California, Japan, New Zealand.

Late Cretaceous (*Laramide orogeny*) : Pyrenees, Dinaric Alps, Tauric Mountains, mountains of Malaya, Sumatra, and New Zealand, Rocky Mountains, Greater Antilles, and Andes.

Lower and Middle Tertiary (*main Alpine orogeny*) : Pyrenees, Alps, Carpathians, Himalayas, and Asiatic Island festoons.

Upper Tertiary to Present Day (*Cascadian orogeny*) : Foothills of the Himalayas (Siwaliks), Banda arc of the Dutch East Indies, St. Elias and the other Pacific Coast ranges of North America, Greater Antilles, New Zealand.

In most of these Alpine orogenic belts two or more phases of movement can be recognised, and in certain regions, particularly in the East and West Indies, orogenic movements seem still to be actively in progress. But taken as a whole the resulting assemblage of mountain systems combines into a

Fig. 208

Map showing the distribution of the Alpine and Circum-Pacific orogenic belts

pattern of striking simplicity. The usual way of expressing this pattern is to describe it as a great ring encircling the Pacific, combined with a Mediterranean belt, of which the chief part is the Alpine-Himalayan system (Fig. 208). On the east the latter swings into the Circum-Pacific ring by way of the Dutch East Indies (the Burman or Banda arc, Fig. 211). Here three arcs come together in spiral fashion in the " Mediterranean " region between Australasia and the extreme south of Asia : (*a*) the New Zealand–New Guinea arc ; (*b*) the Philippine–Borneo arc ; and (*c*) the Banda arc. It is possible that the Kwen Lun and neighbouring ranges north of Tibet

continue across China to join the Circum-Pacific ring south-west of Japan (Fig. 222). At the other end of the Mediterranean belt the Sierra Nevada of Spain and the Atlas are linked through Gibraltar by an inner connecting arc (Fig. 200), but the main ranges remain separate and are cut off abruptly by the Atlantic. Across the Atlantic two corresponding mountain systems appear on each side of the Caribbean Sea (the American Mediterranean) ; a northern one which can be traced from the Cordillera of North and Central America through the Greater Antilles as far as the Virgin Islands, and a southern one, which swings round from the Andes through Venezuela to Trinidad. The two systems, though originally separate, are now being linked by an actively growing arc surrounding the volcanic arc of the Lesser Antilles (Fig. 213). Here the Circum-Pacific ring is being completed by a vast loop which encroaches on the Atlantic. A similar, though much older loop, connects the Andes of Patagonia with the Antarctic Andes of Grahamland. It should be noticed that the Costa Rica–Panama land bridge is of volcanic origin and may possibly not belong to the Circum–Pacific orogenic ring.

Another way of expressing the pattern is to describe it in terms of two gigantic rings (Figs. 209 and 210), one surrounding the northern continents of North America and Eurasia (known collectively as *Laurasia*), the other surrounding the southern land masses of South America, Africa, Arabia, India, Australia, and Antarctica (known collectively as *Gondwanaland*). The first of these rings includes the northern ranges of the Mediterranean belts and the northern half of the Circum–Pacific ring, while the second includes the southern ranges of the Mediterranean belts and the southern half of the Circum-Pacific ring.

Now, as we have seen, the Tethys was a great " Mediterranean " geosyncline which developed between Laurasia and Gondwanaland. Figs. 209 and 210 show that each of the land masses referred to above is rimmed by an orogenic belt wherever it is bordered by the Pacific or by the former site of the Tethys. In plan Laurasia, Gondwanaland, and the Pacific floor all appear to have moved radially outwards,

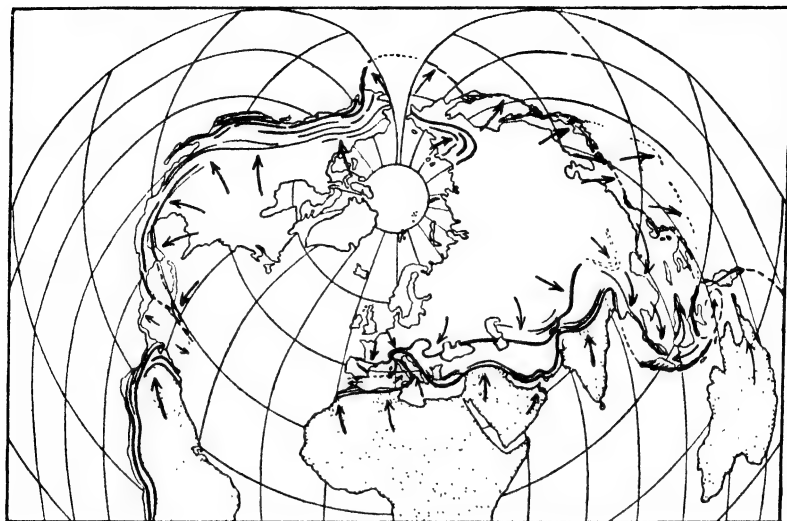



Fig. 209
Map showing the interrupted orogenic ring peripheral to the continental masses (unshaded) of Laurasia. The adjoining blocks of Gondwanaland are dotted. The probable continental movements directed outwards towards the Pacific and the Tethys are indicated by arrows

thus buckling the crust at their margins and forming orogenic belts along these highly compressed peripheral zones. The Tethys itself was obliterated by the approach of Laurasia and Gondwanaland and transformed into the Mediterranean belts.

Within the peripheral ring of Laurasia lie the disruptive basins of the North Atlantic and Arctic oceans, the coasts of which are essentially due to fracture and faulting. Similarly, within the peripheral ring of Gondwanaland lie the South Atlantic and Indian oceans. Here again the coasts are essentially due to fracture and faulting, except in the case of the Burman arc, where the continuation of the Tethys lay along what is now the north-east margin of the Indian ocean. Suess was the first to recognise that the coastal structures of the world were of two contrasted types, which he distinguished as *Atlantic* and *Pacific*. The coasts of Atlantic type are determined by fractures and subsidences which characteristically cut across the "grain" of the lands (*cf.* Fig. 165), though

[Dorien Leigh, Ltd.

(A) The dissected plateau of the Black Forest, from the Feldburg

[A. G. Kilchberg

(B) Frost-splintered peaks of the Mt. Blanc Massif, with the Glacier de Tacul and a large glacial erratic in front

HERCYNIAN MASSIFS

[*F. N. Ashcroft*

The Val Bondasco and the granite peaks of the Bergello Massif (Tertiary). Village of Soglio in the foreground

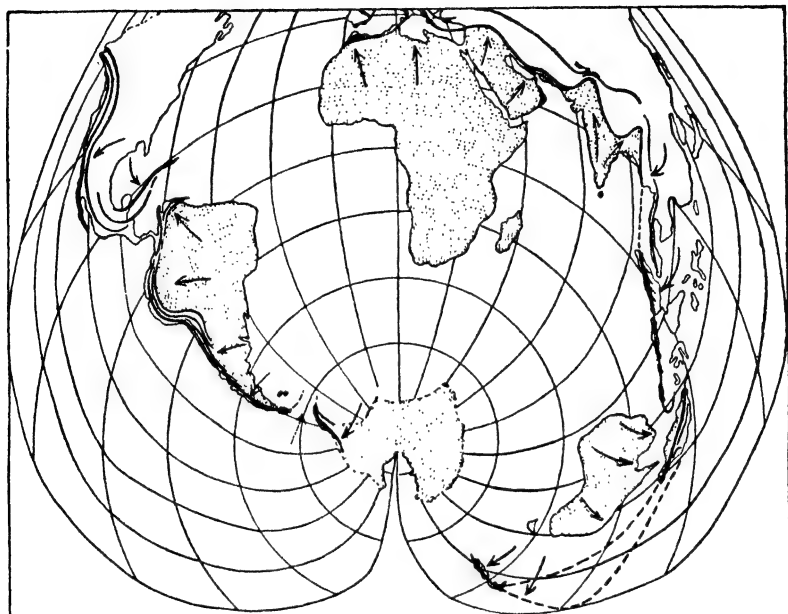



Fig. 210

Map showing the interrupted orogenic ring peripheral to the continental masses (dotted) of Gondwanaland. The probable continental movements directed outwards towards the Pacific and the Tethys are indicated by arrows

locally they may happen to be roughly parallel to one of the older orogenic belts (as in Norway). The coasts of Pacific type are determined by folding and are, in their general outlines, parallel to the " grain " of the lands (*cf.* Fig. 166), being fringed by bordering mountain chains, including island festoons like those of Asia.

The Orogenic Cycle

In every continent there are mountain systems and older orogenic belts of widely different ages. Each of the Pre-Cambrian shields represents a coalescence of successive orogenic belts from which the mountainous superstructure has long ago been removed by denudation. In the Baltic shield there are

four such belts, and six are known in the Canadian shield. The continents have developed by successive orogenic additions to their shields, as illustrated in Figs. 200 and 201.

Detailed study of many of the orogenic belts has shown that, although no two are exactly alike, all can be regarded as variations on a common theme. The theme itself, or in other words, the usual sequence of events involved in the evolution of an orogenic belt, is called the *orogenic cycle*. In general terms it may be summarised as follows :

(*a*) Development of a geosyncline with heavy sedimentation and occasional volcanic activity.

(*b*) Compression of the belt by a first orogenic phase, involving root formation in depth, folding and overthrusting of the superstructure, and uplift of the compressed zone in response to the buoyant (isostatic) effect of the root.

(*c*) Lateral growth of the geosyncline by development of a new subsiding tract outside the rising mountains (Fig. 199). As the latter are carved into peaks and valleys by denudation, they provide much of the sediment which fills up the depression.

(*d*) Renewed orogenic compression of the whole belt. Stages (*c*) and (*d*) may occur twice or even three times (rarely more) in the more complex belts.

(*e*) During the more vigorous orogenic phases, and particularly during the climax of the revolution, the deeper rocks are intensely metamorphosed, and migmatites are formed by hot migrating fluids. Later, granite batholiths are emplaced, followed in some cases by the introduction of valuable ore deposits. These are gradually uncovered by denudation if the cumulative uplift of the completed orogenic belt is sufficiently long maintained.

It sometimes happens, however, that a mountain system is reduced to a lowland or even submerged before much of the superstructure has been denuded (Plate 21A). In such cases the buoyant action of the roots must soon have ceased to function. In other words, the roots themselves must have disappeared, probably by becoming so plastic that, unable to

support the overhead pressure, they flowed out laterally. In response to subterranean changes of this kind the later behaviour of an orogenic belt is generally dominated by epeirogenic movements, often accompanied by volcanic activity. These topics are dealt with in succeeding chapters.

Present-day Orogenesis

As already mentioned, the evolution of certain stretches of the orogenic belts belonging to the Alpine revolution is still actively in progress. Fig. 200 makes it clear that, unlike the Western Mediterranean, which is a sunken median area, the Eastern Mediterranean, the Adriatic, and the plain of Lombardy are depressed regions lying along the " African " front of the Alpine system. South of the Atlas this marginal depression continues on the land, where it is marked by the shotts of Tunisia and Algeria. Towards the east a similar zone of depression can be traced through the alluvial plain of Mesopotamia, the Persian Gulf, and the Gulf of Oman. Still farther east, in front of the Himalayas, the depression reappears in the alluvial plains of the Indus and Ganges. This long zone of subsidence and sedimentation is probably the best example of a marginal geosyncline now in course of development. It illustrates the latest repetition of stage (*c*) in the orogenic cycle.

In the Dutch East Indies the continuation of this geosyncline can be traced for over 4,000 miles in front of the Banda arc (Fig. 211). But here the active belt is very narrow, and stage (*d*)—the stage of orogenic compression—has already been reached. The trend line of this long strip is indicated by an arcuate submarine ridge from which rows of rising islands emerge above sea level at intervals. Proof of recent and continuing movements is furnished by the occurrence on the islands of terraces of upraised coral reefs at heights ranging from sea level to as much as 4,000 feet in Timor ; by transverse fractures and tear faults, pointing to horizontal movements, probably symptomatic of the advance of nappes or recumbent

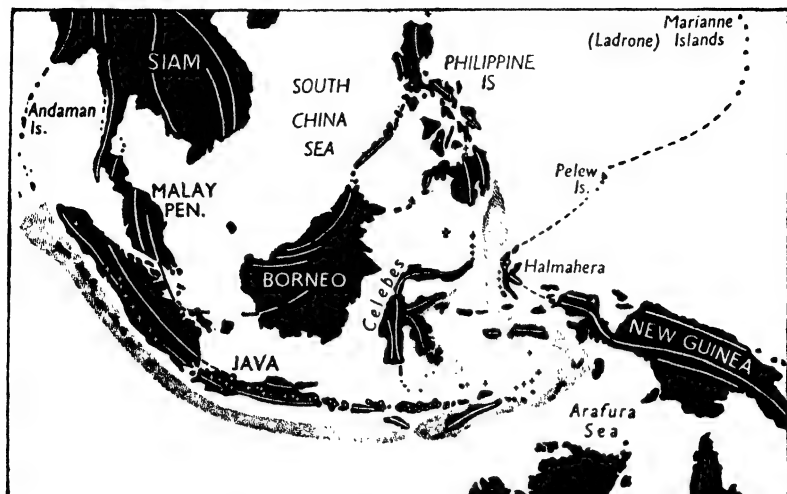



FIG. 211

Tectonic map of the Banda Arc and its links with the Philippine and New Guinea arcs. The belt of negative anomalies of gravity discovered by Vening Meinesz is shown (as far as it has been mapped) by a shading of fine dots. Active volcanoes are indicated by black or white crosses

folds ; and by the extreme liability of the strip to frequent and powerful earthquakes, some of which originate at very great depths.

To all this Vening Meinesz has added a discovery of fundamental significance, made in the course of an expedition (1926) carried out in a submarine lent by the Netherlands Navy for the purpose of making gravity measurements over the sea floors of the East Indies. Meinesz found that the long strip under discussion is characterised throughout its length, but to a width of only 60 or 70 miles, by surprisingly great deficiencies of gravity (Fig. 211). This band of what are called " negative anomalies of gravity " implies that there is a corresponding deficiency of density in the materials of the crust beneath. Only one geological explanation of such a deficiency is consistent with the observed facts : the lighter layers of the crust must have buckled into a great downward fold or root. Fig. 212 illustrates the inferred structure. Obviously a crustal

Fig. 212
Crustal section through Java and the adjoining floor of the Indian Ocean to show the relation between topography, gravity anomalies (broken line with actual determinations indicated by heavy dots), and the inferred down-buckling of the crust. The white arrows in the lower part of the crust suggest the directions of crustal movements thought to be initiated and maintained by convection currents in the underlying substratum (*cf.* Fig. 216)

strip of this kind is far from being in isostatic equilibrium. If it were free to do so, it would be buoyed up into a high mountain range and, indeed, as the islands bear witness, a long series of upheavals has already occurred. The islands are the first visible symptoms of an embryonic mountain chain. But the uplift would be far more spectacular and continuous than it actually is, if there were not, even now, some intensely powerful compressive and downsucking process at work, restraining the tendency of the strip to rise into a position of equilibrium. All the evidence points to the same conclusion : the processes responsible for orogenesis are here still in operation.

A gravity survey of the Caribbean region (1928–1937) carried out by Meinesz and a group of American collaborators in submarines lent by the U.S. Navy, has disclosed the existence of a very similar band of negative anomalies, extending from

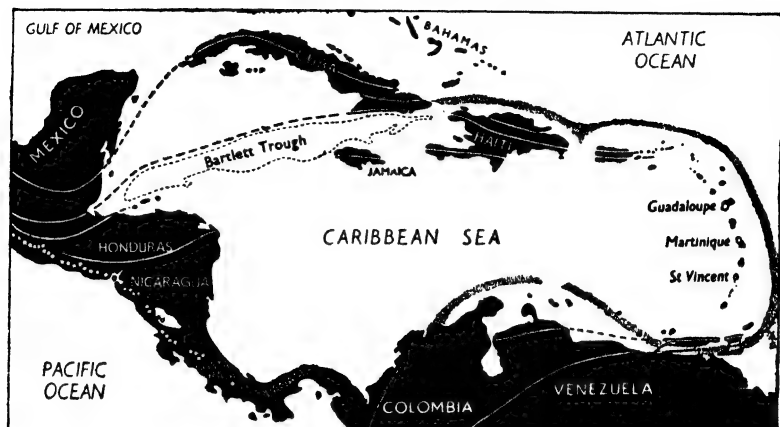



Fig. 213

Tectonic map of the area around the Caribbean Sea, showing the peripheral belt of negative anomalies of gravity (dotted). Volcanoes are indicated by white stars and dots

north of Haiti, round the volcanic arc of the Lesser Antilles, to Trinidad and South America (Fig. 213). Had the war not interrupted this new method of exploring the depths, many other promising belts, such as the Asiatic island festoons, the New Zealand–New Guinea arc, and the loop of the Southern Antilles between South America and Antarctica, might by now have been investigated in this way.

The Cause of Mountain Building

Many attempts have been made to " account for " the remarkable phenomena involved in mountain building, that is, to find some mechanism in the earth competent (*a*) to provide forces of sufficient magnitude to compress, buckle, and thicken the crust ; and (*b*) to explain the sequence of events in each orogenic cycle, the succession of orogenic cycles during geological time, and the distribution of the orogenic belts over the face of the earth. This is a tall order, and discussion of the matter has not yet passed the speculative and controversial

stage. In a body like the earth gravity tends to maintain equilibrium and stability. The only known agency capable of disturbing this equilibrium to any important extent is heat. Increase of temperature leads to expansion and fusion, and decrease to consolidation and contraction. We therefore look to thermal changes within the earth as the most promising line of attack.

We feel reasonably sure that the earth was originally molten, and it is therefore generally believed that the earth has attained its present thermal state, at least on balance, by cooling. This idea provides the basis of the time-honoured *contraction hypothesis*. Once a relatively cold crust was formed, the cooling interior tends to shrink away from it. Obliged by gravity to settle down on the shrinking substratum, and so to fit into a smaller area than before, the crust is inevitably thrown into a state of compression, to which it responds by folding and thrusting. In a similar way the skin of an apple is thrown into wrinkles as the apple dries, and shrinks by loss of moisture.

The contraction hypothesis satisfies condition (*a*) qualitatively if not quantitatively, but is much less satisfactory in relation to (*b*). Some of the objections are as follows :

1. One would expect the crustal wrinkles produced by uniformly distributed compression to be—in pattern—rather like those of a drying apple, instead of being strongly localised, as the actual orogenic belts are. Experiments made to imitate the process as closely as possible confirm this expectation (Fig. 214) and also show that nothing resembling the preliminary geosynclines is reproduced.

2. The cooling of the earth must have been relatively rapid in its early history and have slowed down ever since. Thus the time intervals between the climax of each orogenic cycle and the next should have become steadily longer. But the actual intervals, though all of the same order, suggest a speeding up rather than a slowing down (*cf.* page 109). The Alpine Revolution and all the associated volcanic activity indicate that during the latest cycle the earth has been far more vigorous than at any earlier time for at least 1,000 million years.

3. It is highly improbable that the earth can have cooled sufficiently during the last 200 million years to furnish more than a small proportion of the contraction necessary to match the crustal shortening involved in the Alpine Revolution.

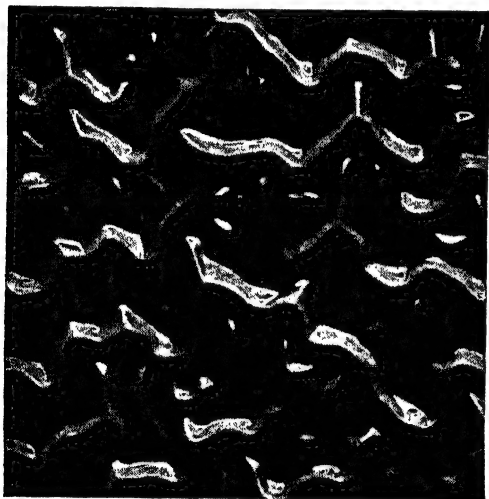
At least in the early stages of the earth's history cooling would be brought about by convection in the substratum. In this process (see Fig. 6) currents of relatively hot and light material ascend in certain places, so carrying heat up to the

[A. J. Bull

FIG. 214

Network of anticlinal ridges produced in a layer of collodion on a stretched circular sheet of rubber allowed to contract in its own plane. (*See A. J. Bull, "The Pattern of a Contracting Earth," Geological Magazine,* 1932, p. 73)

base of the crust, through which some of it escapes by conduction. Towards the top, the currents spread out in all directions from each centre, until they encounter similar currents from neighbouring centres and turn downwards. The descending currents consist of somewhat cooled and slightly heavier material. The driving force arises from the difference in density between the central and marginal columns. This kind of circulation continues until the temperature falls nearly to the freezing point of the material concerned.

Before the discovery of radioactivity it was thought that the stage of convective cooling would not last very long, but

there is now good reason to believe that it may not even yet have ceased. The only essential condition for the maintenance of convection in the substratum is that there should be a small supply of heat available, to make good the heat lost through the crust by conduction and igneous activity. That the earth actually has such a source of internal heat became evident in 1906, when Lord Rayleigh discovered the presence of small amounts of the radioactive elements in a great variety of rocks. The radioactive elements give out heat as they distintegrate (see page 103), whence it follows that heat is continuously being generated within the rocks that contain them. Of the many hundreds of samples that have been tested from all parts of the world not one has been found to be free from these heat-generating elements. The whole of the heat lost from the earth could be supplied by one ounce of radium in every 1,000 million tons of the material of the earth. The rocks themselves contain, on an average, fifty times as much. This startling result indicates that the radioactive elements must be largely concentrated in the crust—otherwise the earth would be much hotter than it is, and we should not be here to discuss the matter—but it provides no reason for supposing that the material of the substratum can be absolutely devoid of these elements. Even minute traces would suffice to keep convection going. Moreover, there is the additional possibility that the base of the substratum may receive a supply of heat from the underlying liquid core. Thus we are free to explore the possibilities that arise from the *hypothesis of sub-crustal convection currents*.

Where currents are flowing horizontally along the under-surface of the crust, they exert a powerful drag on the latter, throwing it into tension where they diverge and into compression where they converge. Thus we should expect orogenic belts to be formed where two approaching currents turn down. This mechanism is particularly well adapted to account for root development and for the localised folding and thrusting of the overlying sedimentary layers. Figs. 209 and 210 strongly suggest that currents arose beneath Laurasia and Gondwana-land and spread out towards their margins, where they en-

countered similar currents belonging to a vast Pacific system. The evidence that roots are still being held down in the East and West Indies indicates that locally, at least, the currents may still be active.

The convective mechanism is not a steady process, but a periodic one which waxes and wanes and then begins again with a different arrangement of centres. After a particular distribution of centres has been established, the rate of flow for a very long period must be extremely slow (Fig. 215). As hotter and lighter material from the base rises to become the ascending columns, and cooler and heavier material from the top turns downwards into the descending columns, the driving force of the currents—and therefore their velocity—is increased. For a comparatively short period the currents move relatively quickly. Towards the end of this stage the hotter material begins to spread out at the top, while the cooler material begins to flow along the bottom. This slows down the currents ; and as hot material moves into the sinking columns and cool material into the rising columns, the currents finally come to rest. Thereafter, a new arrangement of currents begins to develop.

The crustal effects brought about by the three stages of the ideal convection cycle just described correspond closely with the three stages of the simplest type of orogenic cycle :

	Convection Cycle	*Orogenic Cycle*
Stage 1	A long period of slowly accelerating currents	A long period of geosynclinal subsidence over the site of the descending currents
Stage 2	A short period of relatively rapid currents	A short period of root formation and orogenic compression. Downdrag prevents the root from rising into isostatic equilibrium
Stage 3	A period of waning currents, bringing the cycle to an end	A period of gradual uplift and restoration of isostatic equilibrium

In order to study the effects on the crustal layers of convection currents in the substratum Griggs has made a very effective series of experiments with small-scale models, using materials with properties related to the size of the model exactly as the properties of the earth's materials are related

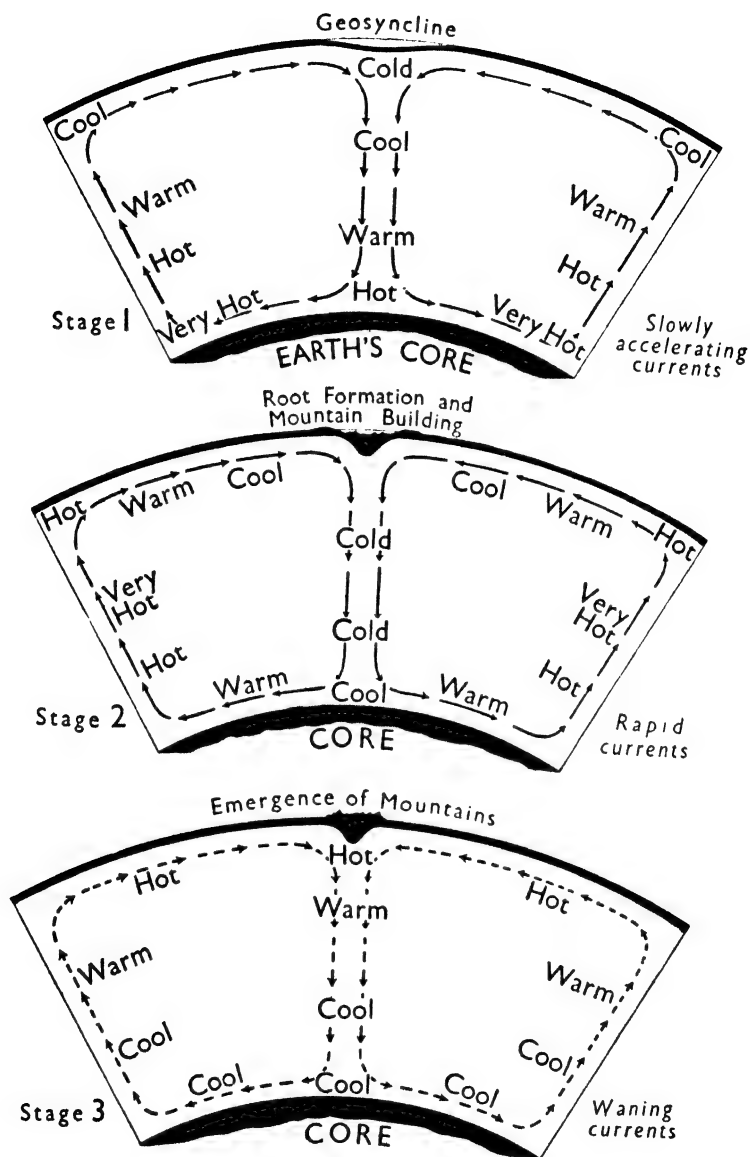



FIG. 215
Sections through the earth to illustrate the possible correlation between the successive stages of an orogenic cycle and those of a hypothetical convection current cycle

to the size of the earth. In one model, designed so that an earth process requiring one million years could be reproduced in one minute, the crust was made of a mixture of sand and heavy oil, while the substratum consisted of very viscous waterglass. To generate the currents rotating drums were used (Fig. 216). When the drums are slowly rotated the crust is gently downwarped by the descending currents (stage 1). As the rotation is speeded up, outward directed thrusts develop near the surface, while the greater part of the crust is dragged inwards and downwards to form a root, which is kept down by the sinking currents (stage 2). As rotation is slowed down and

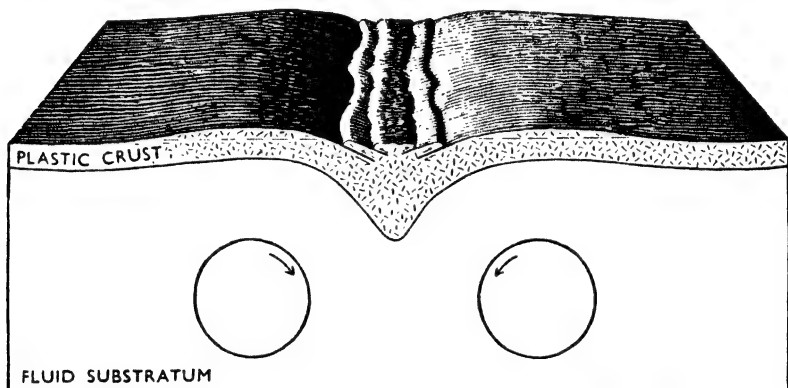



Fig. 216

Diagram of Grigg's dynamic model to simulate the action of subcrustal convection currents and the response of the crust. The stage illustrated shows the development of a crustal downfold (root or tectogene) with outward thrusting near the surface (*cf.* Fig. 197) in response to the currents set up by the rotation of the drums. The substratum in the model is very viscous waterglass, and the continental crust is a mixture of heavy oil and sand (*From* D. Griggs: *American Journal of Science*, vol. 237, 1939, p. 642)

stopped, the root exerts its buoyant effect, and the surface is uplifted well above the original level.

Thus in convection currents we have found a mechanism that closely matches the requirements. Actual currents in the substratum must, of course, be far more complicated than those of the ideal cycle which alone has been considered here —but so are the orogenic phenomena we seek to understand.

In particular, eddies and swirls are to be expected, and one has only to glance at a map of the islands around the Banda Sea (Fig. 211) to realise that their distribution may well be the surface reflection of sub-crustal spiral-like movements.

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Chapter XIX

EARTH MOVEMENTS : PLATEAUS AND RIFT VALLEYS

Surface Expressions of Epeirogenic Movements

We have now to consider the crustal structures, and the resulting modifications of surface relief, brought about by movements of uplift and subsidence. The framework and " grain " of the continental crust are determined by the orogenic belts, but superimposed on this primary framework there are later epeirogenic effects due to warping, fracturing, and faulting of the crust. Here the movements are essentially up and down. The crust behaves somewhat like a flagged or badly cracked pavement on a shifting foundation. Widespread swells and sags—*e.g.* plateaus and basins—are produced by differential warping on a regional scale, characteristically accompanied by marginal and internal faulting ; and ridges and troughs—*e.g.* block mountains and rift valleys—are produced by differential movements of the fault-margined blocks and strips into which the dislocated crust is shattered. The net effect of all these epeirogenic and related movements in recent geological time has been, despite local sinkings and inbreaks, to elevate the greater part of the continental surface well above sea level.

Plateaus are broad uplands of considerable elevation. Tibet and the Colorado and East African plateaus are outstanding examples. *Basins* are relatively depressed regions of roughly equidimensional outline. The term is used very widely and is applied to all broad sags of the crust, whatever the surface levels may be ; from sea basins, like the Black Sea or the Celebes Sea, to mountain-rimmed plateaus which are often, like the Great Basin of Nevada, characterized by internal drainage. Ideally, the drainage from a plateau would be outwards and that of a basin inwards ; but as many

plateaus have locally dimpled or down-broken surfaces and many basins have drainage exits through marginal depressions in the rims, this simple criterion is far from being of general application. The term " basin " is also given to ancient crustal
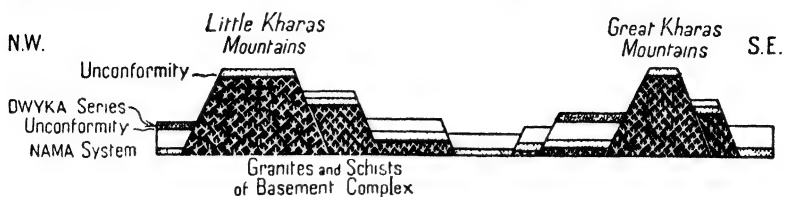
Fig. 217

Diagrammatic section (with minor modifications due to denudation and deposition omitted) to show the faulted structure of the Kharas Mountains, south-west of the Kalahari Desert, South-West Africa. Length of section about 60 miles. (*After C. M. Schwellnus*)

sags which have been filled with sediments and in some cases, as in Africa, subsequently uplifted into plateaus (Fig. 223).

Regions which have been divided by faulting into relatively elevated or depressed blocks are said to be *block faulted.* The upstanding fault blocks, which may be small plateaus or long ridge-like block mountains, are called *horsts* (Fig. 217). The Hercynian massifs of Europe, such as the Vosges and the
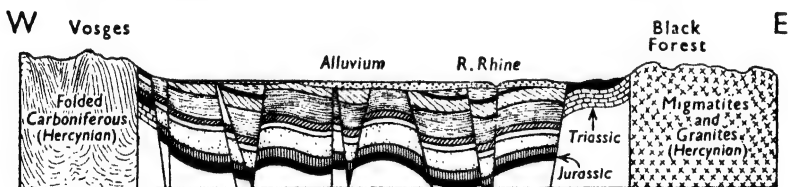
Fig. 218

Section across the Rhine Rift Valley, north of Mülhausen, showing the structure of the rift valley strata as determined by numerous borings. Miocene sediments appear here and there below the alluvium, but most of the beds represented are of Oligocene age, resting on Jurassic, as shown. Length of section about 30 miles

Black Forest (Fig. 218) and the Harz Mountains, are horsts. Blocks which have been tilted, like many of the Great Basin ranges (Fig. 221), are sometimes distinguished as *tilt blocks.* The North Pennine region, as shown in Fig. 39, is an up-

tilted block sloping gently down towards the North Sea. Fault blocks depressed below their surroundings form minor basins or *fault troughs*. A long fault trough, forming a tectonic valley bordered by parallel fault scarps, is known as a *rift valley*. Between the horsts of the Vosges and the Black Forest the Rhine flows through a rift valley (the *Rheingraben*—Fig. 218). The river occupies the valley, but did not excavate it. The most renowned system of rift valleys, however, is that which traverses the East African plateaus from the Zambesi to the Red Sea and beyond (Figs. 223 and 226–28).

In the course of time the surface relief which results from epeirogenic movements becomes greatly modified by denudation and deposition, and locally by volcanic activity. Nevertheless, as illustrated by the examples already mentioned, the face of the earth of to-day is diversified by many new or boldly preserved topographic features which are primarily due to vertical movements. The reason for this is that such movements have been unusually active during Tertiary and late geological time, right down to the present day. Deep gorges are being cut by rivers in high plateaus ; fault scarps are being gradually worn back by the sculpturing hand of erosion ; block mountains are being carved into hills and valleys, and sediments are accumulating in basins and troughs ; but long ages must elapse before the broad outlines of the topography of these regions cease to reflect the latest epeirogenic dislocations of the crust.

The irregular surface of a fractured pavement is due mainly to the varying subsidence of different parts of a poorly laid foundation. Influenced by the idea of a contracting earth, Suess considered the vertical movements of the crust to be also essentially downwards, " sunken " and " uplifted " regions being simply those which had subsided to a greater or less extent than their surroundings. Horsts, according to Suess, are merely blocks left behind in the general down-settling of the crust on the shrinking interior. This conception of the underlying mechanism is no longer acceptable. There is no justification for making any assumption as to whether the up-and-down movements carry the surface of the region

affected away from the centre of the globe or towards it. Some standard of reference there must be, however, and for general purposes sea level is the most appropriate one, whenever it can be appealed to. In dealing with movement along a fault plane such reference may not be possible. The block on one side is said to be downthrown or upthrown relative to the other. Here, each of the adjoining blocks serves as the standard of reference for the other. In the same way a basin or rift valley is naturally described as a region of depression relative to an adjoining plateau or range. The floors of some basins and rift valleys have indeed subsided below sea level (Fig. 225), while in other cases the "depressed" tract may have been actually uplifted, but less so than its surroundings.

Fluctuations of Sea Level

Although sea level is the nearest approach we have to an absolute standard of reference, it must not be overlooked that the level of the sea itself fluctuates from time to time. If the frozen water now locked up in the Greenland ice sheet, and in the far greater one of Antarctica, were to be melted in consequence of a change of climate, the volume of the oceans would be increased and the sea level (allowing for isostatic reactions) would rise by about 100 feet. All the lowlands of the world would be inundated up to this height, and to envisage the resultant consequences to humanity baffles the imagination.

Yet mankind has already lived through even greater changes. During the Pleistocene ice ages, when vast ice sheets covered immense areas of Europe and North America, the level of the sea was about 300 feet lower than it is now (again allowing for isostatic reactions). Broad stretches of land then extended beyond the present shores of all the maritime countries which lay outside the blanketing ice fields. The bottom of the Persian Gulf, for example, must then have been a fertile plain, floored with alluvium from the united waters of the Tigris and Euphrates. This vanished land was, in all probability, the

home of the ancestors of the Sumerian people who immigrated into Chaldea thousands of years ago. We can easily understand why the migration was inevitable. As the last of the former ice sheets began to melt away the sea gradually rose and occupied the Gulf, driving the dispossessed population into the higher ground of Mesopotamia, where the remains of their settlements, long buried by river silt and wind-blown sand, have been disinterred by archæologists.

World-wide changes of sea level, whether due to the growth and decay of ice sheets, to displacement of water by accumulating sediments, or to other causes, are described as *eustatic* changes. In general these are always more or less involved with slow crustal movements due to isostatic readjustments. The removal of an ice sheet, for example, reduces the mass of the crustal column beneath the glaciated area, and in response the region is slowly heaved up until isostatic equilibrium is restored. At the same time, but still more slowly, the ocean floor, now loaded with the weight of the restored water, responds by sinking a little. Moreover, in certain places independent earth movements may be simultaneously affecting the level of the crust. For these reasons the recent changes of level indicated by land emergence—*e.g.* raised beaches—or land submergence—*e.g.* submerged forests—can only in part be referred to eustatic changes. The actual displacement at any particular locality is the algebraic sum of the changes of level due (*a*) to the recent eustatic changes of sea level; (*b*) to the degree of isostatic readjustment so far accomplished at that place; and quite commonly (*c*) to independent earth movements which in some places are still going on.

When the relative movement between land and sea is a few hundred feet or less, it is often difficult or even impossible to disentangle the separate effects of these three factors. In dealing with the major effects of epeirogenic movements, however, this difficulty does not arise, for it commonly happens that the changes of level involved are measurable in many thousands of feet. Moreover, wherever faulting or tilting has taken place it is clear that earth movements have operated, since eustatic changes of level are everywhere uniform.

Dislocations of Orogenic Belts

As we have already seen, the compression of an orogenic belt is normally followed by uplift. This first upheaval of the mountains can be reasonably interpreted as a direct effect of isostatic readjustment, due to the buoyancy of the root. But the root is sometimes quite short-lived. If its heated material softens and spreads out, the mountains subside again over the weak and unstable foundations. Thereafter, the history of the folded tracts and the adjoining areas is one of continued epeirogenic movements of such variety and complexity that no adequate explanation is yet forthcoming. In a general way subsequent uplifts can perhaps be referred to thickening by compression of the weaker parts of the softened foundations, accompanied by widespread uparching and cracking of the overlying layers of the crust. But deep subsidences also occur, and these present a problem for which no satisfactory solution has yet been offered.

The Rockies and the Andes are examples of ranges that illustrate some of these remarkable vicissitudes. They reached their present elevations by comparatively recent uplifts which took place only after the first mountains had already been reduced to low-lying plains. In the high elongated plateaus of the Andes the uplifted plain, now surmounted by great volcanoes, can easily be recognized. Moreover, it is clear that parts of the plain must have been submerged below sea level before the uplift took place, for unfolded Pliocene marine beds are still preserved at heights up to 6,000 feet.

Turning to Europe (Fig. 200) it is apparent that the Hercynian belt has been severely faulted and broken up into isolated upstanding blocks with intervening depressed areas. South-west Ireland is separated from Cornwall and Devon by the western approaches of the Atlantic. Between the horsts of the Vosges and the Black Forest lies the Rhine rift valley. Moreover, as we have seen, much of the broad Hercynian belt subsided at a very early stage to form the floor of the Alpine geosyncline.

Even the Alpine ranges have had their ups and downs.

The Ægean archipelago provides a good example of the fragmentation and partial collapse of a mountain range. Before the Pliocene Greece was directly connected with Crete and Asia Minor. This is proved by the widespread occurrence in the islands and surrounding countries of thick deposits of fresh-water marls crowded with the fossil shells of snails. Lying on these lake deposits there are raised beaches and marine strata of Pleistocene age which indicate subsidence at the time of the first advance of the Western Mediterranean into the Ægean area. At this time also volcanoes broke out, some of which are still active. As a result of more recent faulting and localized uplifts the lake deposits and raised beaches now stand at various levels up to 3,000 feet in the islands and over 5,000 feet near the Gulf of Corinth. Along the shore lines these beds are abruptly cut off, without change of thickness, showing that they must continue beneath the sea. The islands are horsts and between them the sea occupies the intervening regions of collapse. The prevalence of severe earthquakes indicates that the region is still very unstable.

The Black Sea is another region of quite recent subsidence, due in this case to the inbreak of roughly circular areas within a series of arcuate faults. Samples brought up from the floor of the western basin at a depth of over 6,000 feet prove to be Pliocene land deposits. Nearer the present shores there are recent marsh deposits which are now submerged to depths of at least 300 feet. These must have gone down within the last few thousand years.

The Cordilleran Plateaus of North America

The Cordillera of North America includes all the ranges and plateaus west of the Great Plains and of the coastal lowlands of the Gulf of Mexico. The general structure of this long and complex highland region is shown in plan by Fig. 201 and in section by Fig. 219. The Rocky Mountains and their Alaskan and Mexican continuations (folded at the end of the Cretaceous) rise boldly all along the eastern margin (Plate 42B).

[U.S. *National Park Service*

(A) Eroded fault scarp of the Teton Mountains, Wyoming

[*G. A. Grant, U.S. National Park Service*

(B) Aerial view of the Grand Canyon of the Colorado, looking over the Painted Desert and Marble Canyon to the Vermilion cliffs and Paria Plateau beyond

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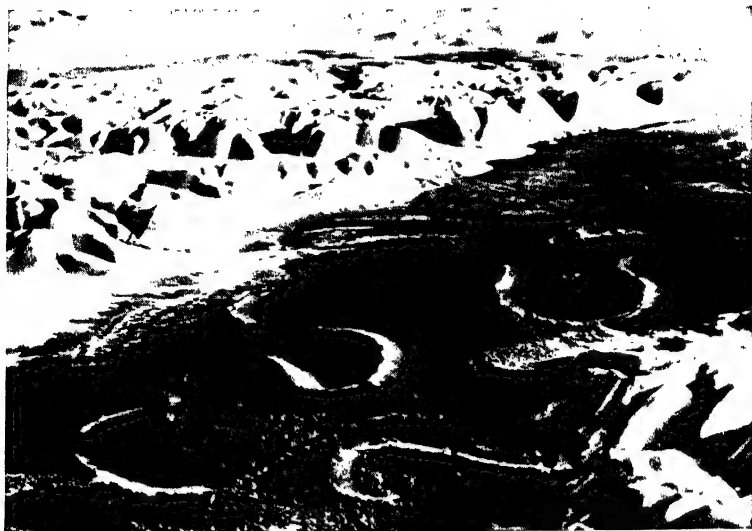
(A) Aerial view of the River Jordan meandering in the floor of the Jordan rift valley

[*Dorien Leigh, Ltd.*

(B) Salt marsh (*salina*) in Death Valley, California (see Fig. 184)

To the west the plateaus are bordered by the Cascade and Sierra Nevada ranges (folded at the close of the Jurassic). Still farther west the Coast Ranges (folded in the late Tertiary and Pleistocene) margin the Pacific.

In the United States the Rocky Mountains represent only one side of the orogenic belt to which they belong. The other side swings out to the west, where it has been transformed by erosion and block faulting into the ranges and depressions of the Great Basin. Farther north a similar tract, buried under a thick cover of plateau basalts, has become the Columbia Plateau. Between the Great Basin and the Southern Rockies lies the unfolded median area of the Colorado Plateau. South of this median area the two sides of the Rocky Mountain orogenic belt unite, the two fronts being represented by the
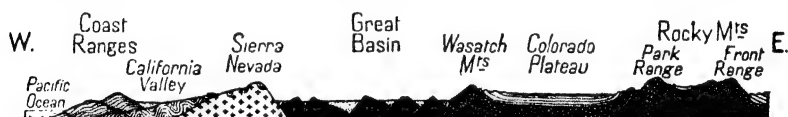
FIG. 219

Schematic section across the Cordillera of the western United States. Length of section about 1,900 miles

eastern and western Sierra Madre. Between these mountain ranges there is no unfolded median area, but the intermontane region has nevertheless developed into the Mexican Plateau. The tectonic history of this plateau is thus somewhat like that of the Great Basin, but it differs in having widespread lava tracts on which, in the south, a series of lofty volcanic cones (including Popocatepetl, 17,520 feet) have been built. In Canada and Alaska the intermontane plateaus, though more constricted, extend through British Columbia to the Yukon.

The *Colorado Plateau* is distinguished by its great height and by the fact that it is built of horizontal or gently undulating sediments. The region was first uplifted with its bordering mountains at the end of the Cretaceous. Deep erosion and accumulation of lake and alluvial deposits occurred during the Eocene. A second uplift, with much dislocation by faulting, took place in Middle Tertiary times, after which the

plateau was again worn down to a plain. The latest uplift has raised the surface to heights of 7,000 to 10,000 feet since the beginning of the Pleistocene.

The Colorado River and its tributaries have cut deep canyons through the Plateau (Plates 1 and 84B). Northwards from the Grand Canyon (see p. 199 for description) the surface rises by successive cliffs and terraces to over 11,000 feet in the high plateau of Utah, the edge of which has been sculptured by erosion into such fantastic landscapes as those of Bryce and Zion canyons (Plate 32A). West of Bryce canyon are the famous laccoliths which are responsible for the updomed hills of the Henry Mountains. To the south of these, on the other side of the Colorado River, is Monument Valley, so called because of its obelisks and towers and other castellated erosion remnants, carved out of red Triassic rocks (Plate 64B). South of the Grand Canyon a considerable area is covered by lava flows and dotted with hundreds of small volcanic cones, now extinct, but so perfectly preserved that they are obviously very youthful features. Not far away from the volcanic area is Meteor Crater, a great depression 4,000 feet across and 500 feet deep, caused by the explosion which followed the impact of a giant meteorite that fell from the sky. This brief outline gives but a faint idea of the variety and interest of the magnificent scenic and geological features for which the region is so justly renowned.

Bordering the Plateau on the north, the *Uinta Mountains* extend at right angles to the Wasatch Range for 160 miles along the Utah side of the boundary with Wyoming. They provide a classic example of subsidence and uplift on a stupendous scale. As shown in Fig. 220, the structure is a broad open anticline, 45 miles across, cut by steep east-and-west faults. The sedimentary rocks are all shallow water types which were deposited, in a deeply subsiding part of the Rocky Mountain geosyncline, to a total thickness of 35,000 feet. Since the Pre-Cambrian foundation of this immense pile is now exposed at a height of 10,000 feet above sea level, it follows that the subsequent uplift has amounted to 45,000 feet. Late Cretaceous uparching of the sediments raised the

crest to about 10,000 feet. During and after this elevation the surface was actively eroded, and Eocene sediments were deposited in the depressions bordering the great arch. The main faulting began at the end of the Eocene and the range was uplifted 25,000 feet, the Eocene deposits being dragged up and strongly tilted at the same time. Erosion continued to lower the surface. Finally the range received a further elevation of 10,000 feet by sharing in the regional uplift which raised the Plateaus during the last million years or so.

The *Great Basin* is, for the most part, an area of internal drainage made up of more than a hundred undrained troughs and basins lying between long block mountains which trend approximately north and south. In the extreme south west
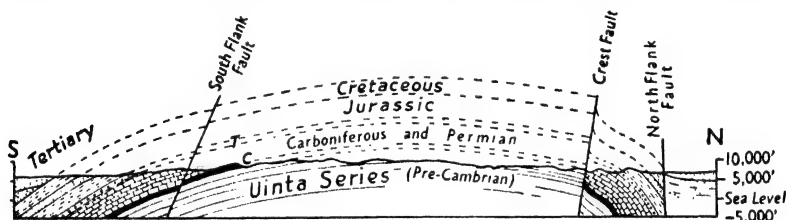
FIG. 220

Section across the Uinta Mountains, Utah. C = Cambrian; T = Triassic

of the area the drainage escapes into the Colorado River at a point which is now the site of the great Boulder Dam. The upstanding blocks, known as the Basin Ranges, rise to heights of 7,000 to 10,000 feet (Plate 84A). The bordering ranges of the Sierra Nevada and the Wasatch Mountains are gigantic tilted blocks of the same type, with their uplifted scarps facing inwards in each case. The floor levels between the ranges rarely exceed 5,000 feet but are usually above 3,000. There are two exceptionally low down-faulted troughs along the western margin. North of the mouth of the Colorado River at the head of the Gulf of California—itself a great depression —is the Salton Sink, 273 feet below sea level. The floor of Death Valley, 200 miles to the north, is just a few feet lower (Plate 85B).

Like the neighbouring areas, the Great Basin region was

reduced to a plain during Tertiary times. The movements and most of the differential faulting which have determined the present topography are post-Tertiary. Along some of the faults there are lines of youthful volcanic cones and, locally, thin sheets of lava have been faulted into strips which now stand at very different levels. Most of the Basin ranges are tilt blocks with steep fault scarps on one side and gentler back slopes on the other (Fig. 221). The older scarps have been considerably eroded into ravines and spurs and the lower slopes are often aproned with screes and fans of rock-waste. Both these and the spurs are truncated by triangular facets along the lower slopes of some of the ranges, showing that
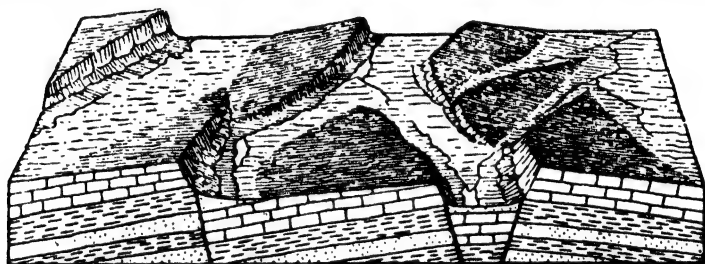
FIG. 221
Diagram to illustrate the fault-block structure of the "basin" ranges of the Great Basin, Utah. (*After W. M. Davis*)

quite recent fault movements have occurred. The severe earthquake of Owens Valley in 1872 was due to faulting of this kind at the foot of the Sierra Nevada.

The basins and troughs are often coated or levelled up with sediment from the ranges. Some are barren desert wastes, others support scanty vegetation, and some contain lakes, mostly temporary. If the basins filled with water until overflow from one to another became possible, an external drainage could be established. But the climate is arid, as the region falls within the rain shadow of the Sierra Nevada. The supply of water is limited and the rate of loss by evaporation is high. Lakes are therefore shallow. Most of them are saline, and surrounded by mud flats known as *playas* or by salt-encrusted flats called *salinas* (Plate 85B). Great Salt Lake, near the

Wasatch Range, is the salt-saturated relic of a much larger fresh-water lake, known as Lake Bonneville, which during the Ice Age expanded to a height of about 1,000 feet above the present level and found an exit northwards into the Snake River. The terraced shore lines of this ancestral lake (*cf.* Plate 63B) form conspicuous horizontal features along the slopes of the many ranges which formed its margins or stood as islands above its surface.

THE PLATEAUS AND BASINS OF CENTRAL ASIA

The surface of Asia has been compared to a bas-relief with a raised pattern of folded and block-faulted mountain ranges on a background of plateaus and basins and marginal plains (Fig. 222). The ranges represent the compressed sediments of former geosynclines. Although the elevation of the present ranges is due mainly to Tertiary faulting and uplift—so that most of the ranges north and north-east of the Himalayas are block mountains—their orogenic folding is far older, except in the south. The Caledonian orogeny was responsible for the folded arcs around Angaraland and for the eastern part of the Altai Mountains. The Hercynian orogeny is well represented in the western Altai and the Tien Shan, and in the bordering ranges north of Tibet, and, less markedly, in their eastern continuations. The folding of the latter, from the Tsinling Shan to Japan was completed in middle Mesozoic times, forming a central mountain belt which now divides China into two natural regions : the desert and loess-covered country of the north and the green and tree-clad lands of the more genial south. The folds of the Himalayas, Burma, and the Dutch East Indies, and some of the Pacific island festoons were added by Tertiary mountain building. Thus the inner ranges are the oldest and the marginal arcs of the south and east are the youngest, with the " negative belt " surrounding the East Indies (Fig. 211) still in process of development.

Asia thus appears to have grown by successive additions to the Angaraland nucleus. The mountain ranges welded
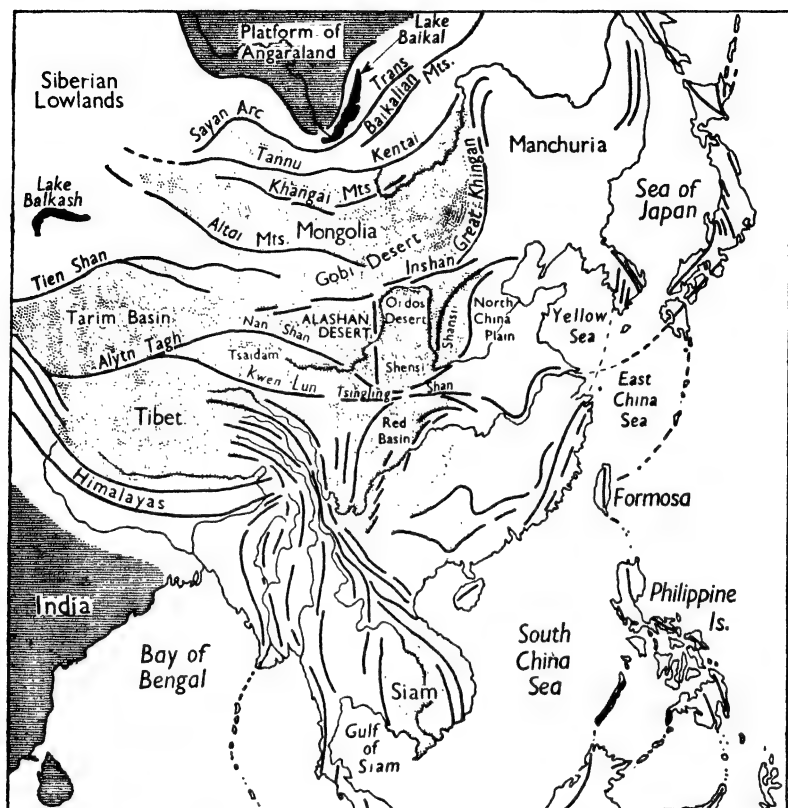
FIG. 222

Tectonic map of Asia, showing the main trend-lines of successive orogenic belts and the intermontane plateaus and basins. The older and more stable regions of Angaraland and India are indicated by horizontal shading

together the formerly isolated areas which are now the intermontane plateaus and basins. It follows that the latter represent the regions that furnished sediments to the geosynclines out of which the mountain rims emerged. With the exception of at least the southern half of Tibet they are not median areas, like the Colorado plateau, but are essentially minor shields or forelands, underlain by very ancient rocks such as the granites and gneisses of Mongolia. The depressions of their warped and faulted surfaces are, of course, veneered with

desert or lake sediments derived from the erosion of their mountainous frames.

Tibet is the loftiest of the world's plateaus, with an average height of 16,000 feet. Nevertheless the southern part lay beneath the Tethys as recently as Cretaceous times. The northern part was already land during the Jurassic. During the Tertiary orogenic cycle the whole region was wedged up, as indicated diagramatically by Fig. 199. The Altyn Tagh and Kwen Lun, although folded long before the Himalayas, were then thrust upwards and outwards towards the Asiatic foreland. Tibet is thus a sort of composite median area. Beyond the steep scarps of the Kwen Lun lies the much lower *Tsaidam basin* (8,000 feet), a desolate waste of stony flats and salt marshes in which the Hwang Ho has its source. In the east and south-east of Tibet several ranges rise above the plateau and swing round towards the south, forming the almost impenetrable barrier of the Great Snow Mountains. Here the Salween, Mekong, and Yangtze Rivers, which rise on the plateau, flow through closely parallel gorges which are amongst the grimmest and least accessible in the world.

To the east of the mountain barrier the country descends by giant faulted steps into the *Red Basin of Szechuan* (1,500–3,000 feet), so called because of the prevalence of brick-red sandstones which were deposited in Tertiary and Jurassic lakes. With its humid climate, productive soil, and mineral resources, this region is the most prosperous province of China. The capital, Chungking, is situated in the south, on the banks of the Yangtze.

North of Tibet the Altyn Tagh drops steeply into the dry and wind-swept *Tarim Basin* (2,000–6,000 feet). The fault scarps face inwards, as also do the precipitous walls of the Tien Shan on the north. The basin is floored with bare gravel and belts of sand dunes. The sluggish and intermittent drainage terminates in the shifting salt marshes of Lop Nor. Formerly the lower parts of the basin were occupied by a vast lake, the shore terraces of which, originally flat, have recently been tilted so that the western end is now 1,000 feet above the

eastern. A subsidiary basin to the north-east encloses the depression of Turfan, 720 feet below sea level.

The Tarim Basin is practically open towards the east, rising by low steps into the Gobi Desert of the *Mongolian Plateau* (3,000–5,000 feet). This vast and largely desert tableland is extraordinarily flat and monotonous. The low ranges of block mountains which traverse it have all been worn down to low relief. On the east the plateau drops abruptly to the Manchurian plains along the steep fault scarp of the Great Khingan.

To the north, Mongolia is bordered by the mountains around Angaraland, within which lies the rift valley occupied by Lake Baikal. The lake floor descends 3,939 feet from a water level of 462 feet, indicating that the bottom of the rift valley is at least 3,477 feet below sea level. Lake Baikal is the world's second deepest lake, and it occupies the deepest known continental inbreak (Fig. 225).

The Plateaus and Basins of Africa

Africa, to which Arabia must be added from a structural point of view, is a vast continental shield, margined with folded mountains only in the extreme north and south. Apart from limited marine invasions across the coastal plains and more extensive incursions of the sea across Abyssinia and parts of the Sahara, Africa has been a land area since the Pre-Cambrian. Throughout this long period the movements of the shield have been persistently epeirogenic, giving a structural pattern of broad basins separated by irregular swells which rise towards the east to form a coalescing series of plateaus, the latter being traversed by a spectacular system of rift valleys (Fig. 223). The plateaus and swells have been intermittently uplifted and denuded, with the result that they now consist of old rocks which were formerly very deep seated. The basins have been the receptacle of thick deposits of continental sediments representing the material eroded from the uplifted tracts.
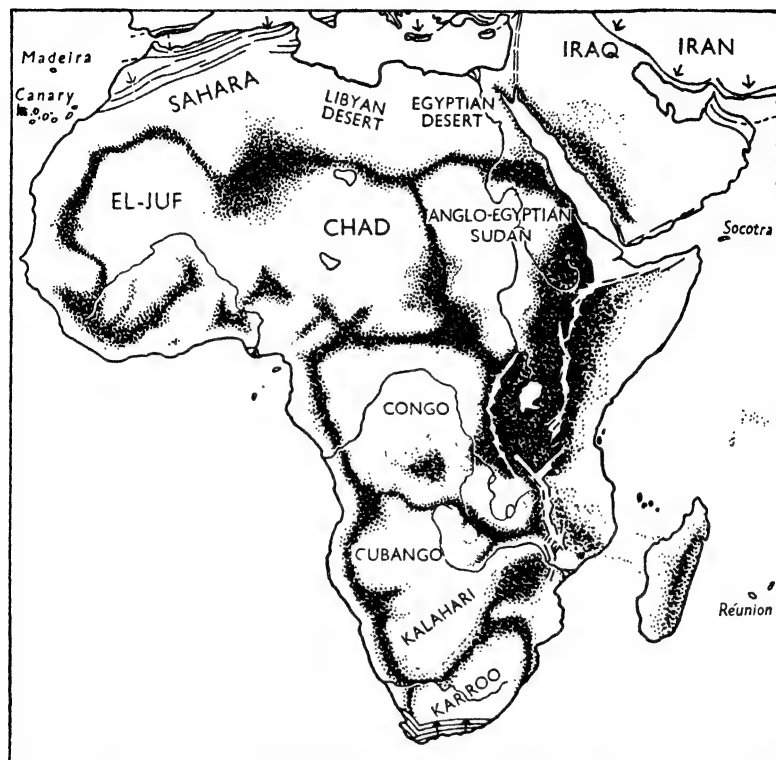
FIG. 223
Map showing in a generalized way the tectonic basins, plateaus, swells, and rift valleys of Africa

Some of the basins are arid regions of internal drainage. The *Chad* basin is one of the most remarkable. Lake Chad, fed by the Shari River from the swell to the south, is a shallow expanse of swamps and open water with no visible outlet. Yet the water is not stagnant, and although evaporation from its surface is high it does not become brackish. Despite appearances, Chad is not a terminal lake, for it drains underground and feeds the oases of the Borku lowlands 450 miles to the north-east. *El Juf*, a vast desert depression north of Timbuktu, is one of the most awesome and least known parts of the Sahara. On the other side of the Equator lies the *Kalahari* basin, partly

grassy steppes and partly desert, with internal drainage in the north towards the brackish swamps of " Lake " Ngami.

In striking contrast is the equatorial *Congo* basin, copiously watered by the great river system after which it is named. The whole region is underlain by thick continental sediments of late Carboniferous to Jurassic age (collectively known in Africa as the Karroo system). These everywhere dip gently inwards from the surrounding swells, as a result of warping which occurred in Tertiary times. The basin as a whole is slightly tilted towards the south-east. Where the Congo meets the swell on the coastal side it forms Stanley Pool, whence it escapes across the obstruction to the Atlantic by way of a series of cataracts. The basin of the *Anglo-Egyptian Sudan* is less easily traversed by the Nile. In the southern part of the basin the White Nile follows a sluggish and tortuous course through a wide expanse of papyrus swamps and lagoons. Thick floating accumulations of vegetable remains, known as the *Sudd* (Plate 75A), obstruct the interlacing channels. These hot reedy swamps are the relic of a former lake, the extent of which is marked by vast spreads of sediment. The level rose until the waters overflowed through a notch in the northern rim, to become the vigorous Nile of the six cataracts between Khartoum and Aswan.

To the east, from the head of the Red Sea to the Cape, Africa has been uplifted into a series of plateaus interrupted by occasional minor downwarps. The basin of the Karroo in the south—the type area of the Karroo system—rises across the High Veld and the Basuto Highlands to the basalt-capped crest of the Drakensberg escarpment. The " Great Escarpment " borders the Interior Plateau of South Africa right round to the west, but nowhere else is it so strikingly developed as in the precipitous walls of the Natal Drakensberg, in places 6,000 feet high (Plate 87A). It should be noted, however, that this escarpment is an erosion feature (page 179), and is not a fault scarp. To the north is the much older basin of the Rand goldfield, with Johannesburg on its northern rim, where the gold-bearing strata dip southwards and are accessible to mining until they sink to depths where the rocks are too hot

to be worked. North of Pretoria is another ancient basin—the great Bushveld igneous complex, illustrated in Fig. 42. Then comes the depression of the Limpopo River, succeeded on the north by the Rhodesian plateaus, drained by the Zambesi, and deeply trenched on the north-east by the Nyasa rift valley.

Farther north is the oval-shaped Central Plateau of Tan-

Fig. 224

Map of Lake Kyoga, Uganda, to illustrate the effect of back-tilting of the plateau east of the Western Rift Valley

ganyika, Kenya, and Uganda. This region was reduced to a peneplain in Miocene times, but it has since been uplifted some 4,000 to 5,000 feet. Even the Central Plateau exemplifies the African habit of basin and swell. Lake Victoria occupies a recent crustal sag (Fig. 229). The lake itself has gently shelving shores, and nowhere exceeds 270 feet in depth, despite its enormous area. The bordering swells are deeply trenched by arcuate series of rift valleys. A significant feature

of the plateau is the characteristic rise of the surface towards the edges of the rifts. The upwarping on the west is so recent that rivers which drained westwards during the Pleistocene are now reversed, so that they flow inwards and drain either into Lake Victoria or into the Victoria Nile (Fig. 224). The curious shape of Lake Kyoga and its swampy margins, filled with papyrus and sudd, is a clear indication that the Kafu River and its tributaries have been ponded back towards a subsidiary dimple north of Lake Victoria.

The Central Plateau is divided from the Abyssinian Highlands by the relatively depressed and block-faulted tract of plateau lavas and volcanoes in which the rift valley of Lake Rudolf is sunk. The lavas continue into Abyssinia, where they surmount Mesozoic marine sediments, all lying horizontally, though now uplifted through many thousands of feet. The Abyssinian rift valleys branch from Lake Rudolf and emerge into the desert plains of Afar, a region which is structurally part of the Red Sea depression, though cut off from the sea itself by a long volcanic barrier (Fig. 227).

The African Rift Valleys

The term *rift valley* was introduced by Gregory for the "Great Rift Valley" of East Africa, which he was the first to recognize as a tectonic feature due to faulting. Gregory defined the term to mean a long strip of country let down between normal faults—or a parallel series of step faults—as if a fractured arch had been pulled apart by tension so that the
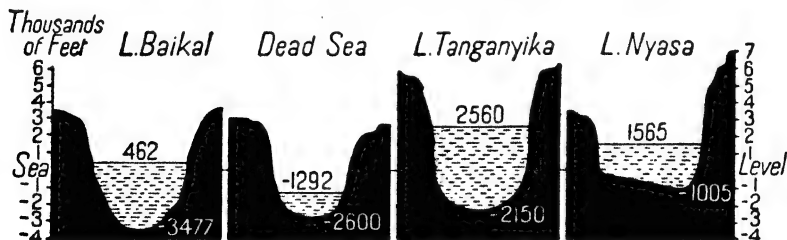
Fig. 225

Sections through rift valley lakes to illustrate local depression of the floor below sea level. Each section is 50 miles across
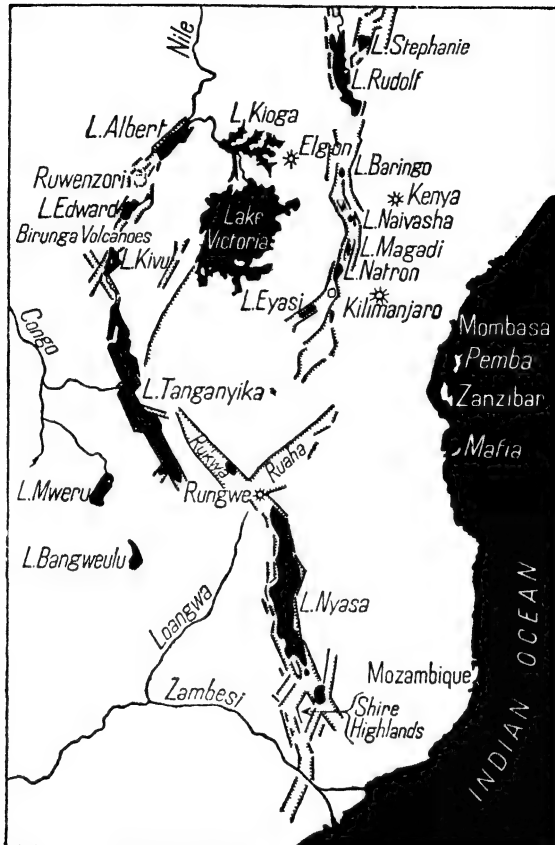
Fig. 226

Map of the Rift Valley system of Africa from the Zambesi to Abyssinia, showing the southern (Nyasa) section and its bifurcation into the Eastern and Western Rifts

keystone dropped in *en bloc* or in strips. The floors of some rift valleys (Fig. 225) have obviously subsided, but in many cases it is equally clear that they have merely lagged behind the surface of the adjoining plateaus in the course of a general uplift. Moreover, there is growing evidence that the orthodox view which associates the inbreaks with tension is far from being of general application. The term *rift valley* is therefore used here without implications as to the mode of origin.

FIG. 227
Map of the Abyssinian section of the Eastern Rift Valley of Africa

The rift valleys do not constitute one long continuous trough with a curving branch to the west, but nevertheless they are all parts of a single system which extends from Syria to the Zambesi, a distance of about 3,000 miles. From south to north the system falls naturally into the following parts (Figs. 226–28) : (*a*) the Nyasa section and its bifurcations ; (*b*) the Western Rift from Lake Tanganyika to Lake Albert ; (*c*) the Eastern or Gregory Rift east of Lake Victoria ; (*d*) Lake Rudolf and the Abyssinian section ; and (*e*) the Aqaba–Dead Sea–Jordan valley section (Plate 85A), with a branch up the Gulf of Suez. Between (*d*) and (*e*) the Red Sea intervenes.

Some of the scarps are old and deeply dissected by erosion, but the most recent ones are steep and sharply defined. In the Eastern Rift lavas preceded and intervened between the successive movements and consequently the older flows, which cover immense areas in Kenya, are themselves faulted. Most of the rift faults follow directions not far from N.N.E. or N.N.W. Trends approximating to N. and S. are less common, and are most characteristic in the extreme north and south.

Fig. 228
Map of the rift valleys and associated faults north of the Red Sea

The association of volcanic activity with the rift valleys is too plain to be missed, but it is tantalisingly variable. In some sections lavas have been erupted on an immense scale, in some only sporadically, but in others not at all. It is curious that some of the deepest troughs, like that of Lake Tanganyika, show no signs of vulcanism. In two of the volcanic regions the alignment of great cones—*e.g.* north of Lake Kivu across the Western Rift (Plate 87B), and from Kilimanjaro (Plate 45) and Meru (Plate 88) to the Giant Craters in the Eastern Rift—suggests that they lie over E.–W. fissures. But no generalization as to distribution is possible. The volcanic mountains of Kilimanjaro and Kenya rise from the plateau well outside the Eastern Rift, while Elgon and its neighbours are situated well on the inner side not far from Lake Kyoga.

There is a remarkable and significant uniformity in the

widths of the rift valleys, as the following measurements (in kilometres) indicate :

Lake Albert	35–45	Dead Sea .	35
Lake Tanganyika (north)	50	Gulf of Aqaba	50
Lake Tanganyika (south)	40	Lake Rudolf	55
Rukwa	55–70	Lake Nyasa .	40–60

Rift valleys in other continents also have similar widths—*e.g.* the Midland Valley of Scotland (Fig. 180), 70–80 ; the Rhine rift valley (Fig. 218), 35–45 ; and Lake Baikal (Fig. 225), 30–70. The Red Sea, with a width of 200–300 km., is obviously a depression of a different order.

Another significant fact about the African rift valleys is that the opposing walls and plateaus are not generally of the same height (see Figs. 225 and 229). In some cases, indeed, the depression is of the trap-door type, with a high wall on one
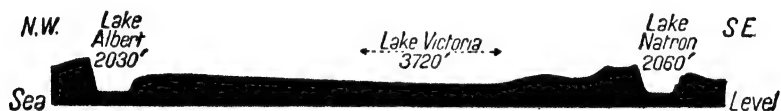
Fig. 229
Section across Lake Victoria and the Western and Eastern Rifts

side and little or no faulting on the other. The floor levels are also highly variable. The Western Rift block varies from 2,150 feet below sea level in the Tanganyika trough to 5,000 feet above sea level south of Lake Kivu, dropping again to less than 2,000 feet in Lake Albert. Lake Kivu occupies a high level valley which would drain to the north, and so to the Nile, but for the fact that the volcanic field of Birunga forms a gigantic lava barrier which has dammed back its waters (Fig. 226). The lake overflows to the south where the river has cut a deep gorge through an older and lower volcanic barrier. It thus drains into Lake Tanganyika, which in turn overflows to feed one of the headwaters of the Congo. An astonishing and unique feature of the Western Rift is the towering horst of Ruwenzori, which rises from within the encircling rift valley to snow-clad peaks up to 16,794 feet—more than 10,000 feet above the general level of the plateau.

[*Dorien Leigh, Ltd.*

(A) Lake Nakuru, with the western walls of the rift behind

[*E.N.A.*

(B) Salt deposits of Lake Magadi

EASTERN RIFT VALLEY, KENYA COLONY

[*S. African Air Force*

(A) Aerial view of the Great Escarpment and Interior Plateau, Drakensberg, Natal

[*C. van Riet Lowe*

Muhavura Mgahinga Sabinyo Mikeno

(B) Extinct volcanoes of Bufumbiro, looking south-west from the plateau, Western Rift Valley, Uganda
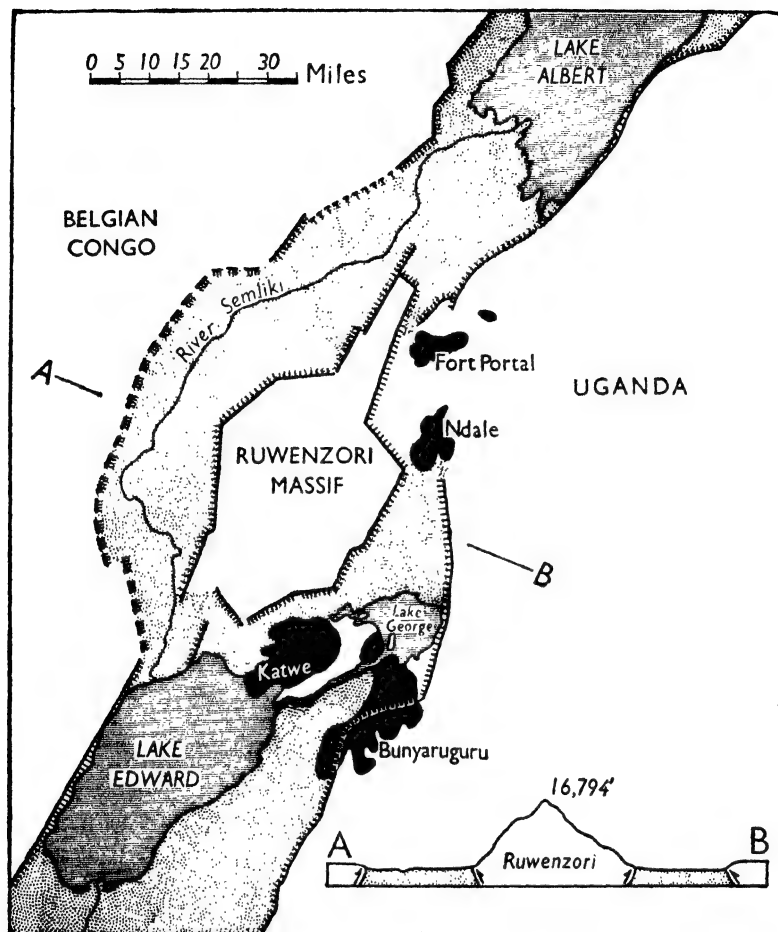
Fig. 230
Map of part of the Western Rift Valley, showing the volcanic areas (black) and the horst of Ruwenzori, a section across which is inset

Ruwenzori is by far the highest non-volcanic mountain in Africa. It is an upwedged block of ancient metamorphic rocks like those of the plateau. Towards Lake Albert the block narrows into a long " nose " flanked by fault scarps. Here recent uplift is proved by the occurrence of a raised terrace of alluvium, which was originally part of the Semliki valley floor.

The Eastern Rift is a region of internal drainage with several independent basins within it due to irregularities of the floor level (Plate 86A). The latter varies from about 3,000 feet in the south to 2,000 at Lakes Natron and Magadi, 6,000 at Lake Naivasha, and 3,000 at Lake Baringo in the north. Lakes Natron and Magadi, and the glaring white salt-encrusted plains around them (Plate 86B), contain vast reserves of soda (Na_2CO_3) and other chemical deposits which are exploited commercially on a considerable scale. The salts are derived from the soda-rich volcanic rocks of the district, partly from the evaporation of the surface waters which drain into the two depressions, but mainly from hot springs. In 1917 the neighbouring volcano of Oldonyo l'Engai actually erupted soda-rich vapours as well as lavas and ashes. A pall of grey volcanic ash permeated with soda settled over a large area, and with the first rains the water holes became fouled with the bitter salts. Many herds of cattle died through drinking from the contaminated pools. The lakes are merely evaporating pans in which the soluble volcanic salts are concentrated.

The Origin of the Rift Valleys

More than a century ago the Rhine rift valley was compared with the fallen keystone of an arch. Thus arose the traditional tension hypothesis, according to which a long wedge-shaped block, tapering downwards, sank between normal boundary faults as the sides were pulled apart. The analogy is a misleading one, however, because a keystone has an empty space into which it can drop until the inward-sloping sides again find lateral support. A rift-valley wedge could not sink unless its weight displaced molten material in depth. Volcanoes would then break out along the cracks. It has long been thought this sort of process may have operated on an incidental scale, but that it could not be an essential part of the mechanism, since, as we have seen, some of the deepest troughs show no signs of vulcanism. However, it has recently been shown by geological work in the Eastern Rift that in

several areas volcanic activity ceased altogether while the rift movements were actively in progress. Such interruptions strongly suggest that the magmatic channels through the crust were then tightly closed by the movements, not widened and further opened as they would necessarily have been according to the tension hypothesis. Moreover, lateral tension fails to account for the fact that the boundary faults are commonly about 35–50 km. apart. The uplift of Ruwenzori is also inconsistent with the tension hypothesis.

These difficulties do not arise on the alternative hypothesis —proposed by Wayland for the Lake Albert and Ruwenzori
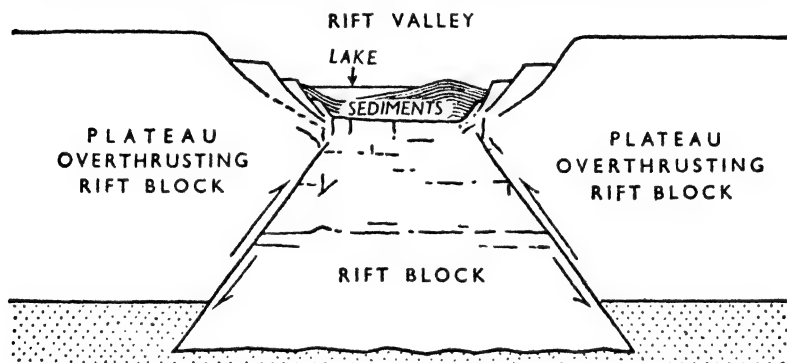
Fig. 231
Diagrammatic section across Lake Albert by E. J. Wayland to illustrate his hypothesis of the origin of rift valleys by compression

sections and by Bailey Willis for the Dead Sea section—according to which rift valleys are produced by deep-seated compression. The boundary faults are then regarded as steep upthrusts and the rift blocks as wedges (widening in depth) held down by pressure from the upriding sides (Fig. 231). It is not to be expected that the thrust faults should be generally visible. As the plateau block rides up a high-angle thrust plane, its forward edge is necessarily left unsupported. Long strips of the overhanging sides slump down, and the visible walls thus appear to be normal faults, often arranged in successive steps. In a few places, where ravines cut through the fault scarps at right angles, subsidiary thrust faults have been

observed beneath the edge of the plateau. Such evidence is not conclusive, however, as these thrusts may have been there long before the rift valleys were formed. More convincing evidence of the operation of compression is provided by the folding of the sediments on the floor of the Lake Albert rift valley (as indicated in Fig. 231).

The results of a gravity survey by Bullard in 1933–34 have thrown much new light on the origin of rift valleys. The plateaus are found to be very nearly in isostatic equilibrium, but over the rift valleys of Lakes Albert and Tanganyika, Rukwa and Magadi, the observed values of gravity, are abnormally low (Fig. 232). Like the "negative
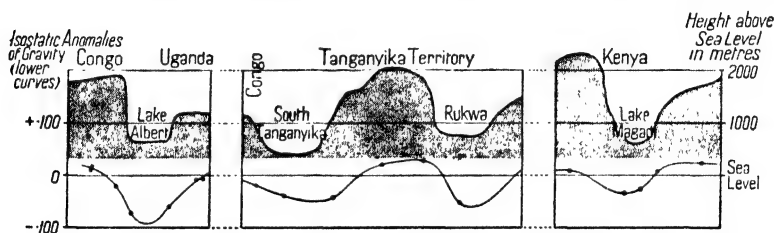
FIG. 232

Sections across four of the African rift valleys with gravity anomalies (determined by E. C. Bullard) plotted below. A marked deficiency is clearly shown beneath each of the rifts

belts" of the East and West Indies (pages 404 and 406), these rift valleys must be underlain by an excess of light material. This important discovery means that if the rift blocks were free to move under gravity—as they would be if the boundary faults were normal faults due to tension—they would rise. It follows that the rift blocks cannot have fallen in under gravity, like a keystone. They must be held or forced down by the plateau blocks on each side, a state of affairs implying sideways compression.

If the rigid crust of the plateau region is compressed laterally, it must first buckle and then (Fig. 233), if the pressure be sufficient, crack at a place A. When fracture occurs, one side is thrust over the other, which is pushed down. After the wall has reached a height of a few thousand feet, a second major

crack occurs, accompanied by thrusting. This takes place at B, where the curvature of the buckled crust is greatest, at a distance x from the first break. Bullard shows that the distance x, the width of the resulting rift valley, is determined by the thickness and elasticity of the crust and the density (say, 3·3) of the substratum. If the thickness is 20 km., $x=39$ km. If the thickness is 40 km., $x=65$ km. The hypothesis thus satisfactorily matches the leading characteristics of rift valleys : their widths and the heights of their walls ; the rise of the plateau towards the rifts ; and the occurrence of lop-sided and single-walled "rifts." An inter-rift block mountain, like Ruwenzori, represents the rare case where the second fracture (or a later one) occurs at a place such as C. The block AC
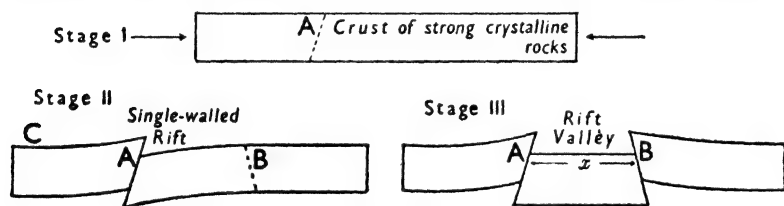
FIG. 233
Diagrams to illustrate the compression theory of the origin of rift valleys. (*After E. C. Bullard*)

is then wedged up, just as a ship caught in the ice of Arctic seas is heaved up by the ice-pressure on its flanks.

The problem of the origin of rift valleys is not yet, however, completely solved. Many competent observers state positively that some of the most clean-cut fault scarps, like the N.E. wall of Rukwa (Fig. 226), are normal faults on far too big a scale to be gravity slumps incidental to underlying thrusts. The part played by volcanic activity is still far from being understood. The pattern of the rift valleys, their relation to the Lake Victoria sag, and above all, their relation to the Alpine orogenic belt in the north have still to be elucidated. The rift valleys of Africa, one of the major tectonic features of the world, provide a magnificent field for future exploration and research.

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Chapter XX

VOLCANIC ACTIVITY

General Aspects

As briefly indicated on page 29, volcanic activity includes all the phenomena associated with the escape at the earth's surface of magmatic materials from the depths. An active volcano is a vent, which may be the orifice of a pipe or fissure, through which the magmatic products are continuously or intermittently discharged. It should be recalled that magma is not merely molten rock : it differs essentially from the latter in being more or less heavily charged with gases and volatile constituents, just as soda water differs from ordinary water. While the magma is confined under a sufficiently high pressure, its gaseous constituents remain dissolved, but as the surface is approached and the overhead pressure is reduced, the gases begin to be liberated, either freely or explosively, according to local circumstances. The molten material emitted at the surface is thus relatively impoverished in gas, and is called lava to distinguish it from the original magma.

In addition to the eruption of hot gases and molten lavas from volcanoes, vast quantities of fragmental materials are often produced by the explosion of rapidly liberated gases. These materials, collectively known as *pyroclasts*, may themselves consist of molten or consolidating lava, ranging from the finest comminuted particles to masses of scoriæ and volcanic bombs of considerable size, or they may be fragments of older rocks (including the lavas and pyroclasts of earlier eruptions), ranging from dust to large ejected blocks, torn from the walls of the feeding channel or from obstructions in the vent. The great clouds of gases, vapours, and pyroclasts that are the most conspicuous feature of explosive eruptions may be luminous or dark, according as the fragmental material is incandescent or not. These " fiery " and " smoky " appearances, together

with the glare reflected from the glowing lavas beneath, were responsible for the formerly popular idea that volcanoes are "burning mountains." Apparently supporting this delusion, the pyroclastic materials that drop from the volcanic clouds often resemble cinders and ashes, by which terms, indeed, they are still commonly described. Actual burning, however, is confined to the almost imperceptible flames of certain gases

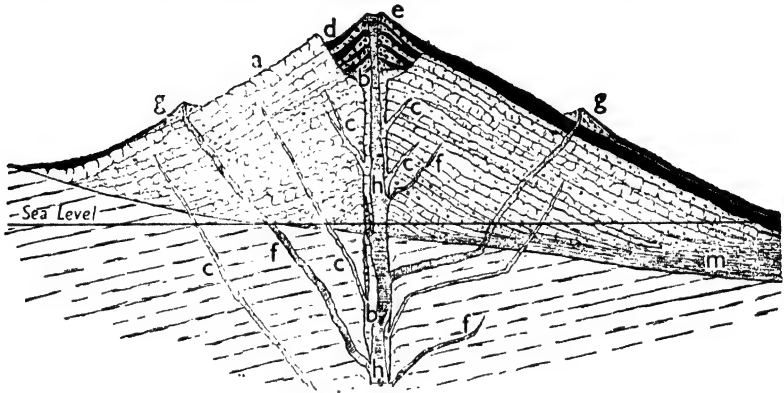



FIG. 234

Diagrammatic section through a composite volcano

The main cone (*a*) is built of lavas and tuffs fed from the conduit (*b*) and braced by dykes (*c*). Formation of an explosion crater (*d*) is followed by growth of an eruptive cone (*e*) fed from the conduit (*h*). Some of the later dykes (*f*) serve as the feeders of lateral parasitic cones (*g*). Marine deposits interstratified with lavas and tuffs are indicated by (*m*)

(*From* James Geikie, *Mountains: Their Origin, Growth, and Decay,* by permission of Messrs. Oliver and Boyd)

such as hydrogen and plays only a secondary part in volcanic activity.

When eruptions take place through a vertical chimney, the orifice is widened into a crater with flaring sides by outward explosion and inward slumping. By the accumulation of volcanic products around the vent a conical or dome-shaped mountain is gradually built up. Volcanoes with the familiar cone-and-crater structure (Fig. 234) are said to be of the *central type,* because the activity is centralized about a pipe-like conduit. Within the walls of their truncated summits

some volcanoes have gigantic depressions which resemble greatly enlarged craters. Such a depression may be due to engulfment of the former superstructure or, less commonly, to the volcano having blown off its own head, and is called a *caldera*. The diameter of a caldera is many times greater than that of the eruptive vent and it is this contrast in size which distinguishes it from a crater (Plates 88 and 94). Nearly all the volcanoes of the present day are of the central type, but at certain periods in the geological past and occasionally during historical times volcanoes of the *fissure type* (Fig. 235) have poured out prodigious volumes of lava from long fissures in the crust, and have smothered the surrounding country in sheets of a far greater order of size than the comparatively limited flows of central volcanoes.

FIG. 235
Part of the Laki fissure, Iceland, showing conelets formed towards the end of the fissure eruption of 1783 (*After Helland*)

A few volcanoes remain continuously in eruption, but in most cases activity is intermittent, and sometimes there are long intervals of repose, during which all signs of activity either cease or are restricted to exhalations of steam and other vapours from vents called *fumaroles*, which at a later stage may pass into geysers or hot springs (see p. 138). As a volcano becomes extinct it passes through similar waning stages. Some volcanoes have even been thought to have become extinct, until a disastrous recrudescence of activity proved otherwise. A striking example is provided by the first recorded eruption of Vesuvius. At the beginning of the Christian era the volcano had slumbered so long that no tradition of its prehistoric eruptions survived. For centuries woods and vineyards had clothed the fertile slopes of the cone and the rugged walls surrounding the grassy floor of the summit caldera were festooned with wild vines. In the year 79 A.D.,

however, after a period of premonitory earthquakes, the catastrophic eruption occurred which overwhelmed Pompeii—a cultured city of 30,000 inhabitants—in an appalling blast of white-hot ashes, and obliterated Herculaneum in torrents of hot mud. It was formerly thought that the seaward part of the caldera was then blown clean away, leaving a half-encircling collar, known as Monte Somma, within which the active cone of the modern Vesuvius has since developed (Plate 92A). However, recent investigations have shown that most of the missing part of the " collar " was blown away during earlier, prehistoric eruptions.

Those who live far from volcanic districts sometimes express surprise that men and women should settle where their crops may be destroyed by vapours and ashes and their fields and vineyards blotted out by streams of lava. But volcanoes are not altogether unfriendly, nor are they uniquely so. Tornadoes, earthquakes, and floods may be equally devastating. Calamities like the horrible doom that overtook Pompeii in 79 and St. Pierre in 1902 (p. 469) are fortunately infrequent. All the volcanoes of the world fail to compete with motor transport as a menace to life—to say nothing of war. And compensating for the risk there is the irresistible attraction of the fertile soils for which volcanic districts are renowned. The decomposition products of the lavas, rich in plant foods, are carried down the rain-washed slopes to the plains beyond, and intermittent showers of ash, if not too heavy, rejuvenate the soil and add to its bulk. This double aspect of volcanic activity—destructive and beneficent—has been recognized from the earliest times of which legendary stories remain.

Volcanic Gases

Steam is by far the commonest of the volcanic gases. Locally the steam may be partly or even wholly derived from ground-waters and crater lakes, but when full allowance is made for these superficial sources there is still ample evidence that the steam liberated in most eruptions is largely of magmatic

origin. Dangerous mud flows may be caused when the torrential rains which descend from clouds of condensed water vapour are accompanied by showers of ashes or sweep loose deposits down the steep volcanic slopes. Gases have been collected from cracks in small blisters of lava formed over gas fountains on the edge of the lava-lake of Kilauea. By this technique contamination by air is avoided as completely as is humanly possible. Besides steam (60 to 90 per cent.) the gases are found to consist, in order of abundance, of carbon dioxide, nitrogen, and sulphur dioxide, and smaller proportions of hydrogen, carbon monoxide, sulphur, and chlorine. Similar gases are liberated elsewhere from active lavas and fumaroles, together with various related compounds, such as sulphuretted hydrogen, hydrochloric and other acids, and volatile chlorides of iron, potassium, and other metals. Incrustations of sulphur and chlorides, as well as of rarer compounds, often in great variety, are deposited on cool surfaces.

An explosive eruption is only the final manifestation of the propulsive power exerted by volcanic gases. Because the density of magma is reduced by the gases held in solution and is still further lowered by the separation of gas bubbles, the magma is enabled to ascend to much higher levels than would otherwise be possible. Another important effect of gases is that of increasing the mobility and prolonging the active life of magmas and lavas. A lava, while still retaining part of the original gas content, may continue to flow until the temperature is down to 600° or 700° C. But when the same lava has crystallized and nearly all its gas has been expelled, the temperature necessary to soften it again is found to be several hundred degrees higher. It follows that loss of gases involves rapid consolidation. The chemical reactions of some of the gases amongst themselves and with oxygen (whether from magmatic ferric oxide or the air) may locally generate heat at volcanic centres and so help to maintain high temperatures and even for a time to increase them. Striking evidence of such heat generation has been described from Kilauea (p. 463).

The source of magmatic gases is not known, but since at least some magmas have formed in the crust from rocks poor

in gaseous constituents, it is probable that additional gases have been contributed from still deeper sources. The ascent of highly energized gases from the primordial sun-born matter of the earth is held by some vulcanologists to be the fundamental cause of volcanic activity.

During geological time volcanic action has probably added considerably to the water in the oceans and to the nitrogen content of the air. Of the immense quantities of carbon dioxide supplied to the atmosphere nearly all has been abstracted by weathering processes and by plant life, and is now represented in the rocks by limestones and coal and related deposits. The chlorine locked up in rock salt and in the dissolved salt of sea water is also very largely of volcanic origin.

Lavas

The temperature of freshly erupted lava is rarely much above the melting-point, and according to the composition and gas content it may range from 600° to 1200° C., the basic lavas, like basalt, being generally the hottest. The mobility of molten lava depends on the same factors. Silica-rich lavas are usually stiff and viscous and congeal as thick tongues before they have travelled far, whereas basic lavas tend to flow freely for long distances, even down gentle slopes, before they come to rest. The speed of a lava stream depends on the mobility and slope, and may, quite locally, reach 50 miles an hour. But such speeds are very rarely attained ; even 10 miles an hour is unusual and often the movement is sluggish. In recent years, when approaching flows have threatened villages on the slopes of Mauna Loa and Etna, the danger has been averted by bombing from aeroplanes, whereby the flows have been constrained to follow new and less menacing courses.

The surfaces of newly consolidated lava flows are commonly of two contrasted types, described in English as *block* and *ropy* lavas, but known technically by their Hawaiian names, *aa* (ah-ah) and *pahoehoe* respectively. Block lava forms over partly crystallized flows from which the gases escape in sudden

bursts. During the advance the congealing crust breaks into a wild assemblage of rough, jagged, scoriaceous blocks. Ropy lava begins at a higher temperature, minute bubbles of gas escape tranquilly and the flow congeals with a smooth skin which wrinkles into ropy and corded forms like those assumed by flowing pitch (Plate 89A and Fig. 236). It sometimes happens that after the upper surface and edges of a flow of this kind have solidified, the last of the molten lava drains away,

[*E.N.A.*

FIG. 236
Pahoehoe lava, Halemaumau, Kilauea

leaving an empty tunnel. Some of the lava caves of Iceland are famous for the shining black icicles of glass which adorn their roofs.

When lava of the ropy type flows over the sea floor, or otherwise beneath a chilling cover of water, it consolidates with a structure like that of a jumbled heap of pillows and is then appropriately described as *pillow lava* (Plate 89B). By the time each emerging tongue of lava has swollen to about the size of a pillow the rapidly congealed skin prevents further growth. New tongues which then exude through cracks in the

glassy crust similarly swell into pillows, and so the process continues. The structure is a common one in the submarine lavas associated with the geosynclinal sediments of former periods, and has been seen actively developing in modern flows that reached the sea floor.

Columnar structure (Plate 3) develops within the interior of thick masses of lava which have come to rest and have consolidated under stagnant conditions. It is especially characteristic of very fine grained plateau basalts which are relatively free from vesicles.

Pyroclasts

The fragmental materials blown into the air shower down at various distances from the focus of eruption according to

[*L. Hawkes*

Fig. 237
Volcanic bombs in ash, Vesuvius

their sizes and the heights to which they are hurled. The coarser fragments, including bombs, blocks of scoria and pumice and blocks of older rocks, fall back near the crater

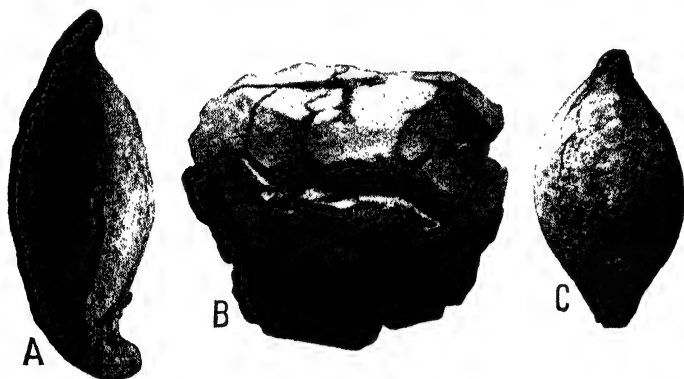
rim and roll down the inner or outer slopes (Fig. 237), forming deposits of *agglomerate* or *volcanic breccia*, the latter term implying that the blocks consist largely of country rocks from the foundations of the volcano. Volcanic *bombs* represent clots of lava which solidified, at least externally, before reaching the ground. Some of them have globular, spheroidal, or spindle-shaped forms due to rapid rotation during flight; others, of less regular shape because they were stiff from the

[*A. Lacroix*

Fig. 238

Volcanic bombs. (A) Basalt, Puy de la Vache, Auvergne ($\frac{1}{8}$ natural size). (B) Bread-crust bomb of dacite, Mt. Pelée, 1902 ($\frac{1}{8}$ natural size). (C) Basalt, Patagonia ($\frac{3}{8}$ natural size)

start, have gaping cracks and are described as *bread-crust bombs* (Fig. 238).

Smaller fragments, about the size of peas or walnuts, are called cinders or *lapilli* (little stones) according to their structure. Still finer materials are referred to as ash. These fall mainly on the slopes and form deposits which, when more or less indurated, are known as *tuffs*. Sometimes showers of augite, felspar, and other crystals that were already present in the lava (before its comminution) fall from the volcanic clouds and contribute to the tuffs. The finest particles, down to dust size, and including shards and splinters of glass, often travel far beyond the cone before they descend. When such material is hurled to great heights and caught up by the wind it may

be carried for immense distances. Microscopic volcanic dust from the catastrophic eruption of Krakatao in 1883 encircled the world, and its dispersion through the atmosphere was responsible for the vividly coloured sunsets that were seen during the following months.

Cones and other Volcanic Structures

The structural forms which result from volcanic activity depend on the quantities, proportions, and characters of the lavas and pyroclasts erupted. Some volcanoes have a dominantly effusive habit, lava being the chief product ; a few are wholly explosive ; but in most cases eruptions of these kinds either alternate or take place simultaneously.

Classification of Volcanic Forms

Explosive	*Mixed*	*Effusive*
1. Explosion vents (maars)	3. Composite cones of pyroclasts and lavas	4. Lava domes of internal growth
2. Ash and cinder cones		5. Lava domes of external growth (shield volcanoes)
		6. Lava plateaus

1. Explosion vents are mere perforations of the crust, marked at the surface by small craters, each surrounded by a low ring of pyroclasts in which fragments of the country rocks are naturally most abundant. In certain recently extinct volcanic districts, such as the Eifel (Fig. 239), Swabia (east of the Black Forest), and the western rift of Africa near Ruwenzori (Fig. 230), groups of these " embryonic volcanoes " form a characteristic landscape, often diversified by lakes which occupy some of the crater basins.

2. When a sufficient supply of fragmental material is furnished an ash or cinder cone is built up. The profile is determined by the angle of rest of the loose material that showers down around the vent. Fine ash comes to rest at angles of 30° to 35°, while nearer the summit the coarser fragments may stand at 40° or more. In 1538 an eruption of ash and pumice suddenly broke out in the country west

of Naples and in a single explosive outburst, lasting only a few days, Monte Nuovo, 430 feet high, was constructed. In 1937 a similar new cone was built up at Rabaul in New Britain.

3. Izalco, west of San Salvador in Central America, is an example of a volcano which began its life as an ash cone in 1770, and has since grown by almost continuous activity into a typical composite cone standing well over 3,000 feet above the surrounding country. All the larger volcanoes around the Pacific and most of those elsewhere are of composite structure,

Fig. 239
Laacher See, Eifel

and with few exceptions they have histories extending over many thousands of years. Composite cones (Fig. 234) are accumulations of successive layers of well stratified tuffs, alternating irregularly with tongue-like lava flows. The lavas are generally andesite or other types that can flow with moderate ease. They may escape through breaches in the crater wall, or through radial cracks which feed parasitic craters—often arranged in linear series—on the flanks. As magma solidifies in the fissures, dykes are formed which help

to strengthen the growing edifice. Etna, the largest volcano in Europe, has hundreds of these secondary vents, and although the summit crater remains a focus of explosive eruptions it is no longer occupied by molten lava.

As already mentioned, a volcano may suffer an eruption of such catastrophic violence that a vast caldera is formed, as if the volcano had blown off its head. If a caldera did in fact originate in this way, fragments of the missing material would form the greater part of the pyroclasts representing the eruption. When, as is usually the case, such fragments are rare, the only alternative explanation is that the vanished part of the cone must have foundered out of sight (Fig. 240).

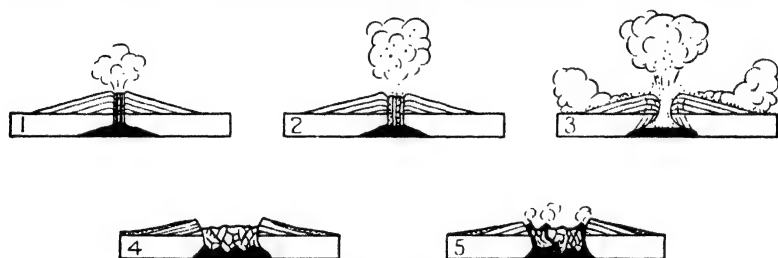



Fig. 240

Sequence of events in the evolution of a caldera of subsidence

(1) Mild explosions (2) more violent explosions (3) culminating explosions and cracking of roof (4) collapse of the cone into the magma chamber (5) growth of new eruptive cones on the caldera floor (*After R. W. van Bemmelen and H. Williams*)

Most of the calderas of composite volcanoes appear to have resulted from the wholesale engulfment of the former superstructure into the space previously occupied by magma, which was rapidly discharged in explosive eruptions of paroxysmal violence. The eruptive vent commonly resumes activity sooner or later and builds up a new cone on the floor of the caldera.

Crater Lake, Oregon (Plate 94), occupies a huge caldera about 6 miles in diameter, formed by the collapse of what was once a lofty composite cone. The cone must have been there not long ago, for it supported glaciers that have left abundant evidence of their former existence on the outer

slopes of the caldera walls. Moraines and glacio-fluvial deposits alternate with beds of pyroclasts; and U-shaped valleys can be followed up to the rim, where they are abruptly truncated by the walls. It is estimated that the ancestral cone must have been about 12,000 feet high, and that since it was sheathed in ice something like 17 cubic miles of the original structure have disappeared. Howel Williams has shown that the catastrophic eruptions that made room for the great engulfment are represented by vast spreads of pumice and scoria, the total volume of which is about 12 cubic miles. Fragments of the old cone itself account for no more than 2 cubic miles. The missing balance may well be finely pulverized material that was hurled high into the air and carried far away by the wind, as happened at Krakatao in 1883. Evidently the frothy eruptible contents of the magma chamber were suddenly expelled by a swift succession of paroxysmal explosions. The conical roof, shattered and unsupported, then foundered into the depths. At some later time a small cone, the summit of which rises above the lake as Wizard Island, was built up by subsequent activity.

Even greater calderas—sometimes referred to as "super-calderas"—occur in Japan and Sumatra. One of the largest of these giant cauldrons, now partly occupied by Lake Toba, is situated at the crest of the Barisan Highlands in N.W. Sumatra. It has an area of about 700 square miles and a volume of about 300 cubic miles. During the late Pleistocene there were paroxysmal eruptions of rhyolite-tuffs, followed later by flows of rhyolite. The tuffs are thickly distributed over 7,000 square miles of Sumatra and they have been traced into Malaya, where their thickness is still 5 to 20 feet. The total volume of the tuffs is of the same order as that of the cauldron itself, which came into existence as a result of the titanic outbursts. It is thought that an upward-expanding granite batholith arched up its roof when it had nearly reached the surface and that the gas-laden magma near the top eventually blew itself out through fissures in the roof. What was left of the roof then subsided into the eviscerated head of the batholith.

4. The shapes of volcanic structures built wholly or dominantly of lava flows depend on the fluidity of the lava concerned. The more silica-rich lavas, such as rhyolite, dacite, and trachyte and the corresponding obsidians, are often so highly viscous that they cannot flow far from the vent. Steep-sided and sometimes even bulbous domes are then constructed immediately over the pipe. Because of the obstruction further growth takes place mainly by additions from within, the outer layers being cracked and pushed aside by the internal expansion. Sarcoui (Fig. 241) and some of the other puys of the Auvergne, and the " mamelons " of Réunion (north of Madagascar), are notable examples of domes of internal

[*L. Hawkes*

Fig. 241
Dome of Sarcoui, Auvergne

growth. Similar domes form in the craters of certain composite volcanoes by the slow upheaval of stiff lava occupying the conduit. As cracks develop, obelisks and spines of lava are squeezed through the top and may reach heights of hundreds of feet before they are demolished by gas expansion within them or by explosion from below. A dome of this kind rose in the crater of Mont Pelée during the disastrous eruption of 1902, and by its tenacious obstruction of the vent led to one of the most dangerous types of explosive activity ever known (p. 462). Later, the plug of the conduit was forced bodily upwards, through the dome, thus forming the celebrated " spine " of Mont Pelée (Plate 93B).

5. Highly fluid basaltic lavas, from which gases escape so easily that explosive activity becomes subordinate, spread out as thin sheets for great distances. By the accumulation of

[*Aircraft Operating Co. of Africa*

Aerial view of the caldera wall, inner conelet, and eruptive vent of Mt. Meru, Eastern Rift Valley, Tanganyika Territory

[H. C. Mendenhall, U.S. Geol. Survey

(A) Cascades of *pahoehoe* lava, Kilauea, Hawaii

Crown Copyright Reserved] [*H.M. Geol. Survey*

(B) Pillow structure of an ancient submarine lava, now exposed on a glaciated surface near Tayvallich, Argyllshire

successive flows in various directions a wide-spreading dome with gentle slopes, rarely exceeding 6° or 8°, is constructed. The classic examples of these *shield volcanoes* are those of the Hawaiian Islands ; others occur in the Samoa group and in Iceland. Hawaii (Fig. 242), the largest of the island chain to which it belongs, has been built up from the sea floor by the coalescence of several shield volcanoes. Mauna Loa is the

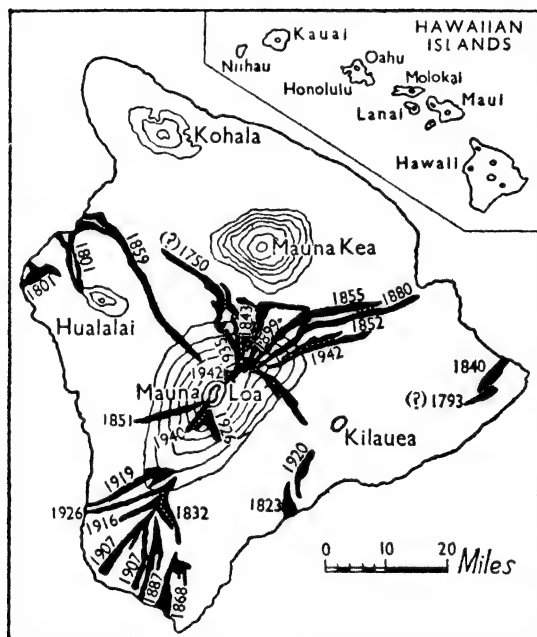



Fig. 242
Map of Hawaii and its recent lava flows

highest, rising 30,000 feet (nearly 14,000 feet above sea level) from a broad base 70 miles in diameter. Kilauea lies on its flanks, 20 miles from the summit and 4,000 feet above the sea. The " craters " are calderas of subsidence containing deep pits often occupied by swirling lakes of lava, open to the sky. These sometimes overflow, but at other times the lava drains away through deep fissures, to emerge lower down on the slopes, sometimes below sea level. When an underlying magma

chamber is thus temporarily emptied, the roof is left with diminished support. Caldera development then takes place by foundering within arcuate faults, and the pits themselves become enlarged by the caving in of slices of the walls.

6. In many volcanic belts the central volcanoes have a well-marked linear distribution, suggesting that they are fed from long deep-seated fissures. Owing to varying degrees of obstruction, the magma rises to very different levels along a fissure and finally breaks through at isolated points where the overhead resistance was least or where gas fluxing through the rocks was most effective in opening a passage. The vents thus localised afterwards tend to persist. In regions subjected to powerful crustal tension, however, deeply penetrating fissures may provide uninterrupted channels for the swift ascent of enormous volumes of basaltic magma. Flowing nearly as freely as water, the lava pours out through long rents and floods the surrounding country, forming sheets that come to rest with almost horizontal surfaces. Individual sheets may average only 20 to 100 feet in thickness, but by repeated eruptions from swarms of fissures vast basaltic plateaus thousands of feet thick have been accumulated in the past, covering areas up to half a million square miles.

The largest area of plateau basalts in the British Isles is that of Antrim (Plate 17A and Fig. 243), but this is only a small part of the far greater Brito-Arctic region (Fig. 252), extensive areas of which were flooded with basalts during early Tertiary times. Although considerable tracts have foundered and are now beneath the sea, 60,000 square miles still remain in Antrim, the Inner Hebrides, the Faroes, Iceland, and East and West Greenland. Shield and other types of volcanoes arose later at certain localities, including Iceland, where activity still persists. In our own islands, especially in Mull, Ardnamurchan, and Skye (Plate 18B), we see only the basal wrecks of the ancient volcanoes, worn down to their roots by millions of years of denudation.

Plateau basalts covering areas of 200,000 square miles or more occur in the Columbia and Snake River region of the

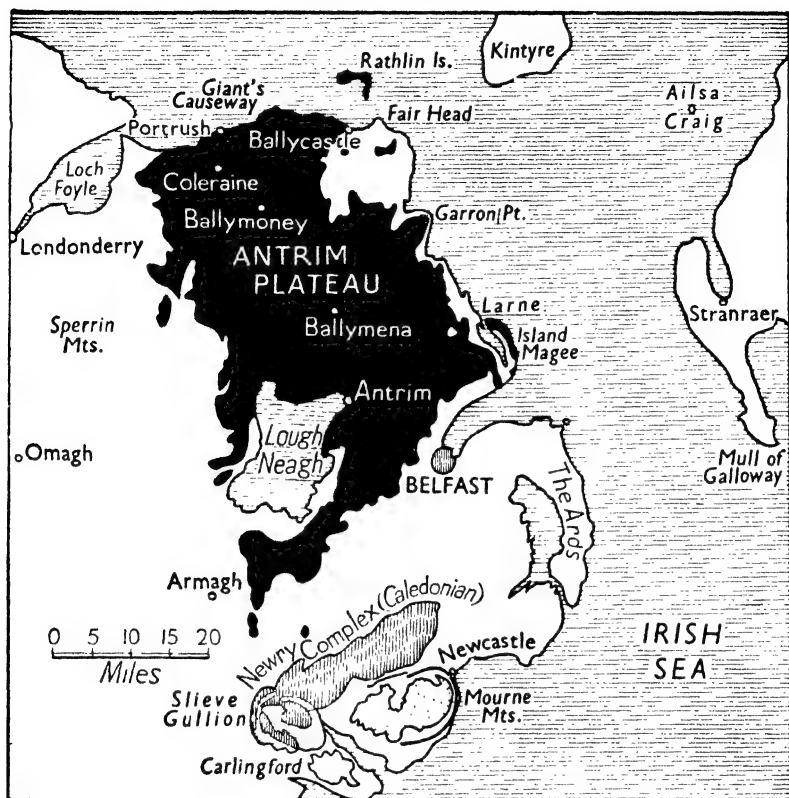



Fig. 243

Map of north-eastern Ireland showing the Tertiary plateau basalts (black), the Tertiary intrusive centres of Mourne, Slieve Gullion, and Carlingford (dotted), and the Caledonian Newry Complex (broken vertical shading)

north-western United States (Miocene to Recent), the Deccan of India (early Tertiary), and the Paraná region of South America (Jurassic). Other vast areas which were flooded with basalts in Jurassic or Tertiary times occur in Mongolia and Siberia, in Arabia and Syria, in many parts of Africa (*e.g.* Abyssinia, around the Victoria Falls, and along the Drakensberg behind Natal), and in parts of Australia (see Fig. 252). Where the flows thinned out and denudation has since removed them, the underlying rocks are seen to be penetrated by swarms

of dykes representing the feeding channels of the vanished flows. In many other regions, notably in the Karroo of South Africa, similar basaltic magmas failed to reach the surface, but riddled the stratified rocks just below with innumerable dykes and sills. Altogether, more than a million cubic miles of basalt have been transferred from the depths during the last 150 million years or so.

During historical times Iceland has been one of the few regions in which fissure eruptions have been witnessed. The greatest basalt flood of modern times broke out at Laki during the summer of 1783. From a fissure 20 miles long torrents of gleaming lava, amounting in all to three cubic miles, overwhelmed 218 square miles of country, and sent long fiery arms down the valleys beyond. As the activity diminished in intensity, obstructions choked the long rent, gases accumulated instead of effervescing freely, and small cones were formed at intervals at points from which the waning lava continued to exude (Fig. 235).

Types of Central Eruptions

Eruptions vary widely in character according to the pressure and quantity of gas, and the nature of the lava from and through which it is released. Several well-defined phases have been recognised, of which the following are the chief (Fig. 244) :

Hawaiian Type.—Effusion of mobile lava is dominant and gas is liberated more or less quietly. From the surface of a lava lake jets and fountains of incandescent spray may be thrown up by the rapid emission of spurting gases (Plate 90B). When caught by a strong wind the blebs of molten lava are drawn out into long glassy threads known as *Pele's hair*, Pele being the Hawaiian goddess of fire.

Strombolian Type.—When less mobile lava is exposed to the air in a crater, the pent-up gases escape more spasmodically, with moderate explosions which may be rhythmic or nearly continuous. Clots of lava, often incandescent, are blown out, to form bombs or lumps of scoria, while in phases of more

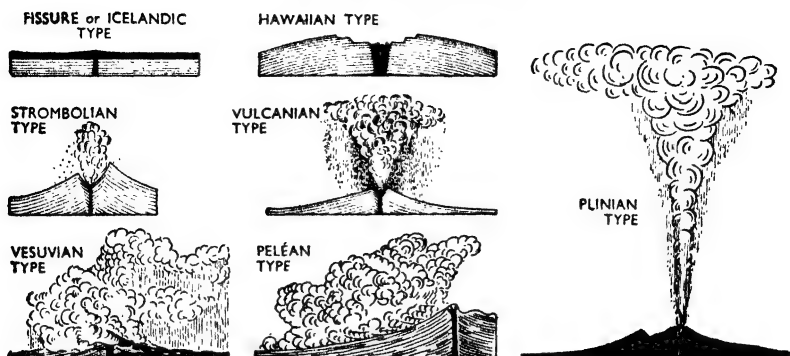



Fig. 244
Diagrams to illustrate the chief types of volcanic eruptions

intense activity the magmatic explosions may give rise to luminous clouds. Stromboli, one of the Lipari Islands north of Sicily, normally behaves in this way, its minor eruptions recurring at short intervals ranging from a few minutes to an hour or so.

Vulcanian Type (named after Vulcano, also in the Lipari group).—The lava is more viscous and pasty, and quickly crusts over between eruptions. Gases accumulate and gather strength beneath the congealed cover and blow off at longer intervals, with correspondingly greater violence. The resulting volcanic clouds are dark, and characteristically assume a convoluted or " cauliflower " shape as they ascend and expand. The major eruptions of many volcanoes begin with a vulcanian phase whenever an obstructed vent has first to be cleared out ; and they may end in the same way, when the waning activity is just sufficient to throw out material which has avalanched into the vent from the unstable crater walls.

Vesuvian Type.—This is a paroxysmal extension of the Vulcanian and Strombolian types, the new and specific feature being the extremely violent expulsion of magma which has become highly charged with gas during a long interval of superficial quiescence or mild activity. In consequence of the preliminary removal of the contents of the pipe down to a con-

siderable depth—often as a result of the escape of lava through lateral fissures and vents—the overhead pressure on the underlying magma is relieved. The magma then bursts into an explosive froth and expels itself as vast luminous clouds of " cauliflower " form. These ascend to great heights, and from them showers of ashes are widely distributed (Plate 2).

Plinian Type.—The most violent Vesuvian eruptions sometimes culminate in a stupendous blast of uprushing gas, which rises to a height of several miles, and there spreads out into an expanding cloud of globular masses of gas and vapour. This phase was first observed by Pliny during the catastrophic eruption of Vesuvius of A.D. 79.

Peléan Type.—Here the limit of high viscosity and explosiveness is reached. Upward escape is prevented by the growth of an obstructive dome above the conduit (page 468). Intermittent spurts of tightly compressed magma force a passage through lateral cracks, and each of these sweeps down the slopes as an intensely hot avalanche of self-explosive fragments of lava, lubricated by constantly expanding gases and vapours. These downward-rolling explosive blasts, one of which wiped out St. Pierre in 1902, are commonly referred to as *nuées ardentes* (Plate 93A). They may be either dark or incandescent, and are not always " glowing " as the French term suggests. Perret, who has observed them at close quarters, defines a *nuée ardente* as an " avalanche of an exceedingly dense mass of hot, highly gas-charged and constantly gas-emitting fragmental lava, much of it finely divided, extraordinarily mobile, and practically frictionless, because each particle is separated from its neighbours by a cushion of compressed gas."

KILAUEA

Kilauea is a low basaltic dome—no more than a slight undulation—on the eastern flanks of Mauna Loa (Fig. 242), with a steep-walled caldera, about three miles in diameter, sunk in its flat summit. The active vent in the caldera floor

is the deep fire-pit of Halemaumau (Plate 90), in which the lava column alternately rises and falls, occasionally disappearing out of sight, sometimes crusting over, but generally forming a lake of surging lava, which presents a magnificent spectacle at night as dazzling pools and streaks break through the duller ruddy surface and burst into spraying fountains. On account of its easy accessibility and relative freedom from danger, Kilauea has become the most closely investigated of all volcanoes.

In 1912, during a period when the pit was full to the brim, Day and Shepherd measured the temperature of the lava and found that in the course of 23 days it rose from 1070° C. to 1185° C. Over the same period a steady increase in the rate of gas discharge was observed, culminating at the time of highest temperature in the maximum development of lava fountains, of which over 1,100 were seen playing simultaneously over the surface. As the level of the lake had not varied, it was concluded that the increase of temperature was due to heat generated by chemical reactions, involving the more active of the uprising gases. By collecting and analysing the gases it was found that reactions of the kind inferred must have been inevitable. The potent source of heat thus revealed was however, mainly superficial, for later measurements showed that the temperature at the surface was about 100° C. higher than that of the lava at a depth of 20 feet.

For several years the rise and fall of the lake did not exceed some 700 feet. In 1924 the lava withdrew to a much greater depth, clearly as a result of drainage through subterranean fissures. Earthquakes occurred 30 miles to the east and beyond, and finally, out on the sea floor along the same line of disturbance, the lava found an exit. The walls of Halemaumau, no longer sustained by lava, avalanched into the pit while it was emptying, thus enlarging it at the top and choking it at the bottom. Ground-water seeped into the debris, passed into high-pressure steam, and so removed the successive obstructions in a series of violent explosions (Plate 91A and Fig. 245). Such explosive activity probably occurs in Hawaiian volcanoes only on the rare occasions

when the underlying magma falls far below the level of the ground-water.

When the pit was thoroughly cleared out, it was found that the avalanches and explosions of a few weeks had increased its surface dimensions from 800 × 500 feet to 3,400 × 3,000 feet.

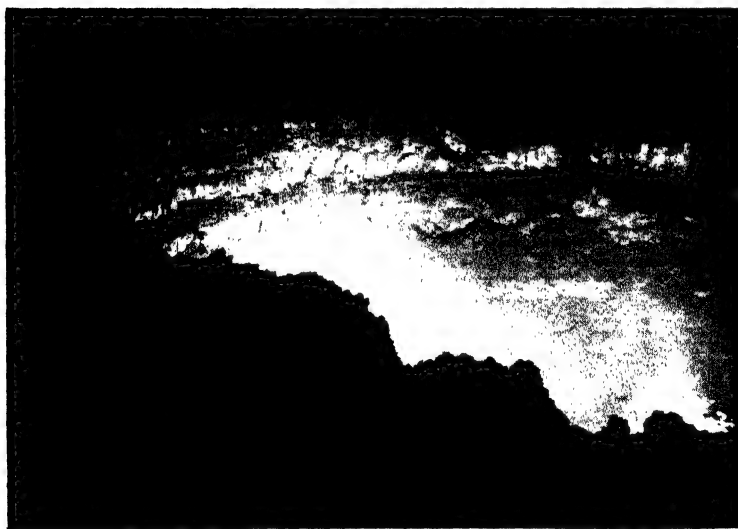
[*H. T. Stearns, U.S. Geol. Survey*

FIG. 245

Explosive eruption from the pit of Halemaumau, May 22, 1924. Photo taken from the Hawaiian Volcano Observatory on the edge of the caldera of Kilauea

The floor of the great cauldron, 1,300 feet below the edge, was seen to consist of solid, well crystallised rock, steaming vigorously, but showing no sign of a central conduit for the lava. Only small feeding channels and gas vents could be detected in the walls, and when the lava began to return it first broke

[*I. C. Russell, U.S. Geol. Survey*

(A) Lava lake at a high level

[*E.N.A.*

(B) Lava lake at a low level, showing the top of a lava fountain (Photo taken by the glow of the molten lava at 3 a.m.)

HALEMAUMAU, KILAUEA, HAWAII

Am. Mus. Nat. History, N.Y.

(A) Explosive eruption of Halemaumau, Kilauea, 1924 (see Fig. 245)

[*E.N.A.*

(B) Anak Krakatao, between Sumatra and Java

through a scree of volcanic debris as a brilliant fountain that spurted to a height of 175 feet. Halemaumau is evidently a collecting chamber fed by a number of relatively small channels leading back into the inaccessible regions from which the magma ascends. In 1929 fountains 200 feet high were observed, and for a time the lava rose in the pit at about 5 feet per hour. So far, however, in the present cycle of activity the fluctuating level of the lake has not yet succeeded in reaching the rim of the now greatly enlarged pit.

Vesuvius

During the sixteen centuries that followed the eruption of A.D. 79 Vesuvius broke into violent eruption only ten times, each outbreak being followed by a prolonged period of quiescence. With the eruption of 1631, after 130 years of repose, the volcano assumed its modern habit of continual, but cyclic activity, the cycles being marked by definite crescendoes leading to outbursts of paroxysmal intensity at intervals which so far have varied from 11 to 40 years. The last two of these major eruptions occurred in 1872 (Plate 2) and 1906 (see footnote on p. 468).

Throughout the 1906 eruption, Frank Perret, most courageous of vulcanologists, remained at the observatory on the western slopes, and his intimate record of the sequence of events has become one of the classics of geological literature. In 1905, when the eruption was already threatening, the cone fissured high up on the north-west slope (A, Fig. 246), and thus led to an emission of lava which temporarily relieved the tense conditions in the crater. On 4th April 1906, the cone was fractured at much lower levels (B–G, Fig. 246), and torrents of gas-saturated lava gushed out. The effect of the relief of pressure beneath the crater was a terrific intensification of roaring explosions which kept the whole mountain in a continuous state of powerful vibration. White-hot lava, torn into fragments, was projected for miles into the overhanging ash cloud, like a fiery effervescing geyser. Intense electric dis-

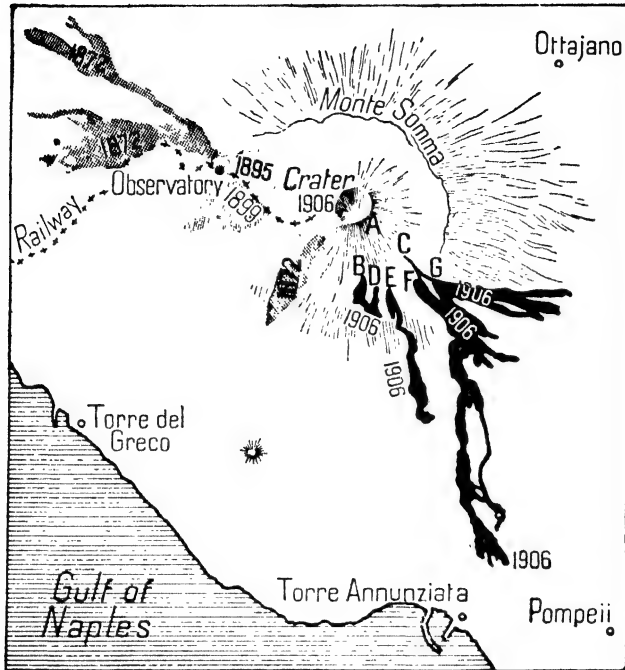



Fig. 246

Vesuvius and Monte Somma showing the points of emission of lava in 1905 (A) and 1906 (B—G)

charges added to the lurid glare. At one stage a formidable jet of projectiles shot over Monte Somma, and brought disaster to the towns on the plains beyond.

Four days after the paroxysm—the Vesuvian phase—began, it culminated in a mighty uprush of gases—the Plinian phase (Fig. 244)—which continued for the greater part of a day, blasting out the throat of the chimney, tearing away the upper portions of the cone, and reaching a height of 8 miles before spreading out. The level from which the gases were escaping must by now have descended into material too " solid " to be expelled from the volcano. An enormous volume of this medium must, however, have been drained to feed the prodigious blast. As the gas pressure gradually became less overwhelming, the walls of the widened crater began

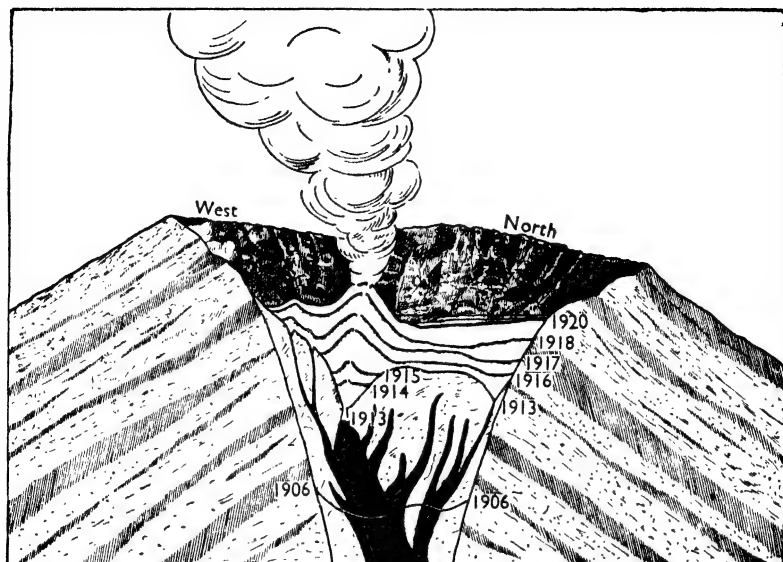



Fig. 247
Diagrammatic representation of fourteen years' growth of the active conelet of Vesuvius after the eruption of 1906

to fall in, creating temporary obstructions and thus leading to powerful explosions and the generation of dark Vulcanian clouds heavily charged with ash. This concluding stage of the eruption persisted intermittently for several days, during which the intensity gradually declined. By 22nd April the eruption was over.

During the next few years the deep funnel of the crater was gradually filled up by avalanches from the walls. The floor of debris first came into view in 1909. Apart from the emission of vapours, the volcano remained in repose until 1913, when incandescent lava perforated the floor, and began to build up a new eruptive conelet (Fig. 247). Since then Vesuvius has been continuously active, long periods of quiet effervescence of the lava within the crater of the conelet alternating with occasional outflows which, on the whole, have tended to become more voluminous as the years have passed (Fig. 248). Judging from the past behaviour of the volcano it would appear

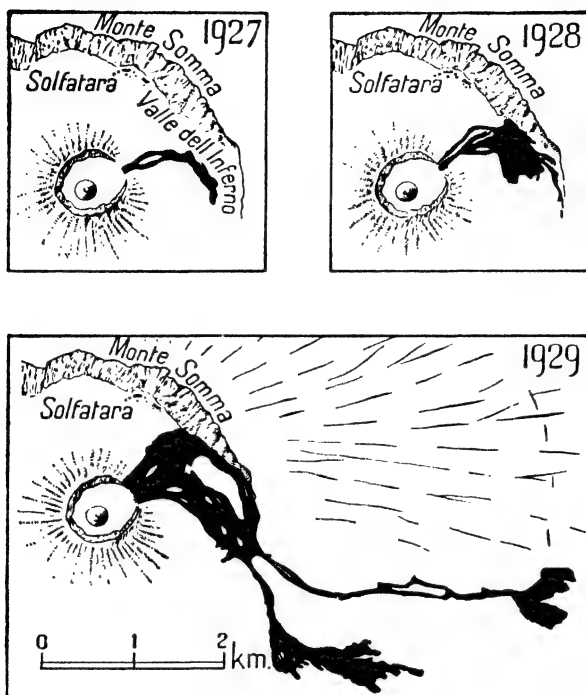



FIG. 248

Sketch-maps showing the lava flows from Vesuvius in three recent years

that the crescendo of activity is approaching the climax of another major eruption.*

MONT PELÉE

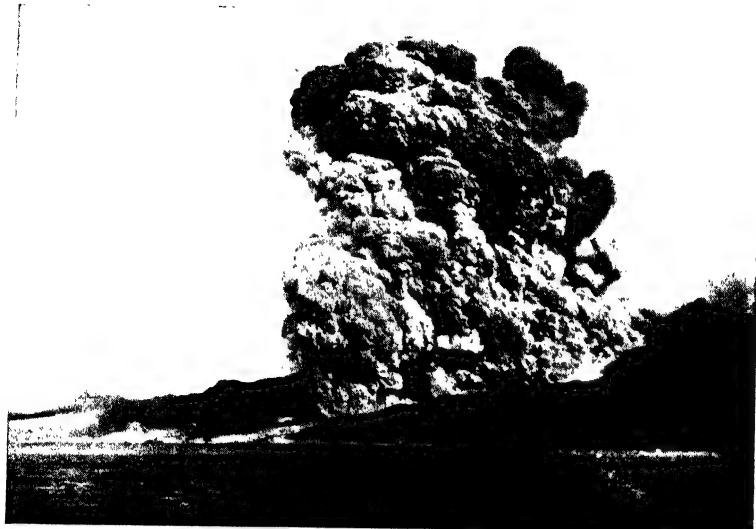
Before the tragic catastrophe of 1902, Mont Pelée (Martinique, in the volcanic arc of the Antilles) had long been dormant, the only previous activity known to the inhabitants having been quite moderate Vulcanian eruptions in 1792 and 1851. In the early spring of 1902 Vulcanian explosions again broke through, but this time the open crater so formed was soon filled up and sealed over from within by the growth

* Since this sentence was written the threatened eruption has actually occurred (March 1944).

[Fox Photos, Ltd.

(A) Vesuvius and Monte Somma, 1918

[Fox Photos, Ltd.

(B) Crater of Vesuvius and eruptive conelet, 1918

[*A. Lacroix*

(A) *Nuée ardente*, 16th December 1902

[*A. Lacroix*

(B) The spine of Mt. Pelée, 1903. Ruins of St. Pierre in the foreground

MONT PELÉE, MARTINIQUE

of a dome of extremely viscous lava. The deeper, highly explosive magma then began to escape at intervals through lateral cracks, each outburst forming a detached globular mass which rapidly expanded into a *nuée ardente* (Plate 93A), sweeping down to the sea with the violence of a hurricane. Most of these were directed towards the west, but on 8th May an exceptionally powerful *nuée* unexpectedly burst out towards the south. St. Pierre, the capital of Martinique, lay across the track, and within a few minutes the whole city and its 30,000 inhabitants were utterly annihilated by the irresistible, asphyxiating blast (Plate 93B). In the harbour ships turned turtle and sank in the boiling sea. After this unparalleled disaster activity continued for many months, but all the subsequent *nuées* followed their earlier track.

In October the plug of viscous lava in the chimney began to be forced bodily upwards, and a gigantic steaming column rose high above the crater-dome. Presently half of it broke away along a slanting crack from the summit, the part that remained thus assuming the shape of a spine. The latter reached a height of about 900 feet above the dome in the course of seven months, but by July in the following year it had crumbled to pieces as a result of gas expansion within it, gas fluxing around its base, and ordinary weathering.

Only two days before St. Pierre was wiped out a similar devastating eruption occurred in the island of St. Vincent to the south. After a series of violent earthquakes the crater lake of the Souffrière volcano boiled and overflowed, and a black *nuée*, heavily charged with incandescent masses of lava, descended from the summit and destroyed everything in its path. Here the death roll amounted to about 1,600.

From 1929 to 1932 Mont Pelée again became active, the preliminary symptoms being earth tremors and rumblings and increased emission of gases and vapours from fumaroles. Soon after the eruptions had started Perret took up his quarters on the volcano, and kept it under watchful observation. He was soon able to reassure the population—most of whom had fled after the first *nuée* appeared—and the normal business of St. Pierre was gradually resumed. The eruptions followed a

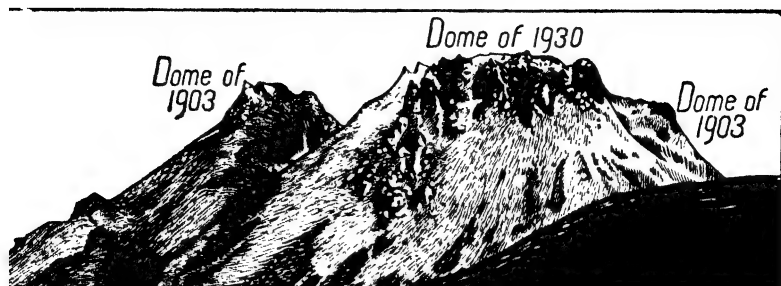



FIG. 249
View of the growing dome of Mt. Pelée in 1930, showing spines in various stages of protrusion and collapse
(*Drawn from a telephoto taken from St. Pierre by F. A. Perret*)

remarkably rhythmic course, periods of *nuée* discharge alternating with periods of dome formation with very little overlapping. Innumerable spines of viscous lava were squeezed through the dome during its phases of growth (Fig. 249), but within a short time, never more than a few days, each of them collapsed into fragments which slithered down the ashy slopes. The *nuées* all descended to the sea along a valley well to the north of St. Pierre.

KRAKATAO

For two centuries before its impressive awakening in 1883 (Figs. 250 and 251), the old volcanic wreck of Krakatao (in the Sunda Straits, between Java and Sumatra) had been dormant. In May of that year the vent of Perboewatan became active, Vulcanian explosions being followed by eruptions of moderate Vesuvian type. During the next few weeks many new vents were opened around Danan, until by August at least a dozen Vesuvian eruptions were in progress, and steadily increasing in violence. The climax was reached during the last week of August. On the 26th formidable detonations were heard every ten minutes. Dense volcanic clouds reached a height of 17 miles and ashes, transformed into stifling mud by the incessant rain, fell over Batavia, which was plunged into thick darkness, relieved only by vivid flashes of lightning.

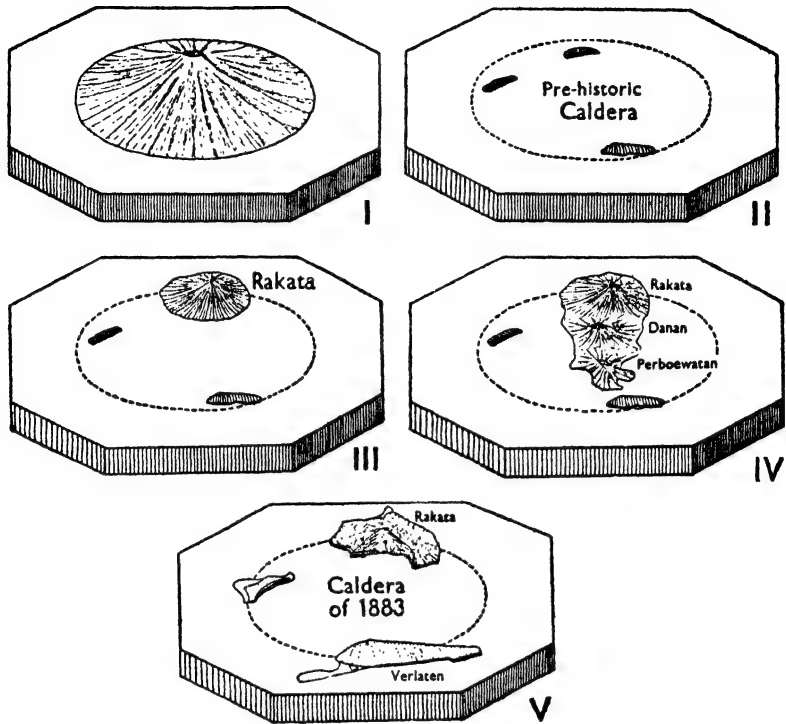



FIG. 250

Block diagrams illustrating five stages in the history of Krakatao
(*After B. G. Escher*)

I Original andesitic cone of Krakatao

II After explosive evisceration, probably accompanied by collapse of the superstructure, a great caldera was formed, rimmed by three small islands

III Growth of Rakata, a basaltic cone

IV Krakatao before 1883, after two later andesitic cones had coalesced with Rakata

V After the 1883 eruptions. Later eruptions have since built up the island of Anak Krakatao within the caldera

On the morning of the 27th came four stupendous explosions, the greatest of which was heard 3,000 miles away in Australia, and a vast glowing cloud of incandescent pumice and ashes rose 50 miles into the air. Although Krakatao was uninhabited, the catastrophe did not forgo its toll of life. Enormous

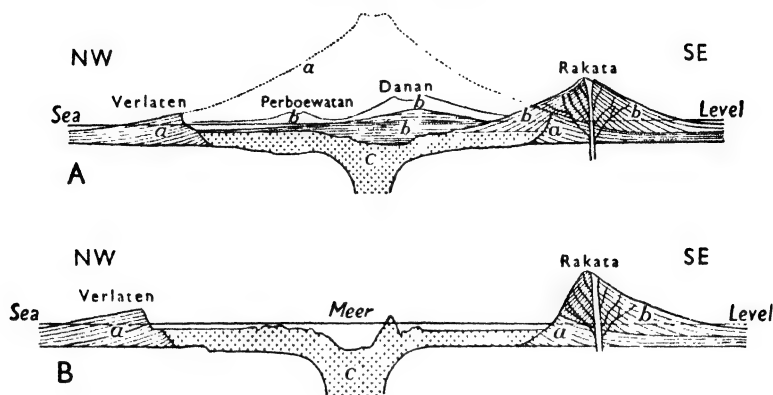



Fig. 251

(A) Profile of Krakatao before 1883, with a dotted indication of the original cone, of which relics *a* remain on Verlatan and near the base of Rakata; *b* represents the lavas, etc., of the later cones (stages III and IV of Fig. 250), and *c* the gas-charged magma basin responsible for the 1883 eruptions. (B) Profile of Krakatao after the eruptions of 1883. In this section *c* mainly represents the materials that collapsed into the eviscerated magma chamber

sea waves, one of them 120 feet high, swept over the low coasts of Java and Sumatra and 36,000 people were drowned.

When Krakatao again became visible, it was found that two-thirds of the island had disappeared. Subsequent survey showed that a deep submarine hollow had taken the place of eight square miles of land. It was originally thought that the greater part of the island—amounting to about 4 cubic miles—had been blown away by the colossal explosions. When the surrounding deposits of tuff came to be examined, however, it was found that they contain less than 5 per cent. of material representing the vanished rocks. All the rest, consisting of glassy ash and pumice, is a product of the magma that was responsible for the eruption. Thus it was, for the most part, not the rocks of the volcanic cover, but the contents of the underlying magmatic reservoir that were blown away. The cover then subsided, leaving a vast island-rimmed submarine caldera, 4 by 4·5 miles across, at the surface.

After remaining dormant for 44 years, a new active vent (Plate 91B) broke through the caldera floor late in 1927 and

continued to erupt at intervals until 1933, building up a cinder cone known as Anak Krakatao (*Anak*, "child of"). It is of interest to notice that the material erupted in 1883 was dacite, averaging 65 per cent. of silica, whereas the bombs and lapilli from the new vent were basalt, averaging 52 per cent. of silica.

The Distribution of Volcanoes

Nearly five hundred volcanoes are known to be active or to have been in eruption during historical times, but besides these many thousands of extinct cones and craters are still so perfectly preserved that they must equally be taken into account in considering the distribution of recent vulcanism. Reference to Fig. 252 shows that a high proportion of the late Tertiary to still active volcanoes are situated in or near the Circum-Pacific and Alpine-Himalayan belts of the latest orogenic cycle. Another noteworthy association with profound crustal dislocations is illustrated by the past and present vulcanism within and adjoining the African rift valleys and their continuations north of the Red Sea. Other scattered lines and groups of volcanoes occur in the Pacific, Atlantic, and Indian Oceans.

Two-thirds of the active volcanoes and an immense number not long extinct are distributed around the borderlands and island festoons of the Pacific. The accompanying list indicates the active occurrences by numbers (excluding merely parasitic

South-Eastern Continuation of Alpine-Himalayan Belt

Sumatra (11)
Java (19)
Lesser Sunda Is. (15)
Moluccas (3)

Circum-Pacific Girdle

Aleutian Is. and Alaskan Peninsula (35)

Kamchatka (9)
Kurile Is. (13)
Japan (33)
Philippines (98)
S.E. New Guinea and islands to N. (15)
Solomon Is. (2)
New Hebrides (7)
Tonga (6)
Kermadec (1)
New Zealand (4)

W. Canada (–)
W. United States (1)
Mexico (9)
Guatemala (14)
Nicaragua (7)
Costa Rica (5)
Lesser Antilles (9)
Northern Andes (11)
Central Andes (9)
Southern Andes (22)
Southern Antilles (2)

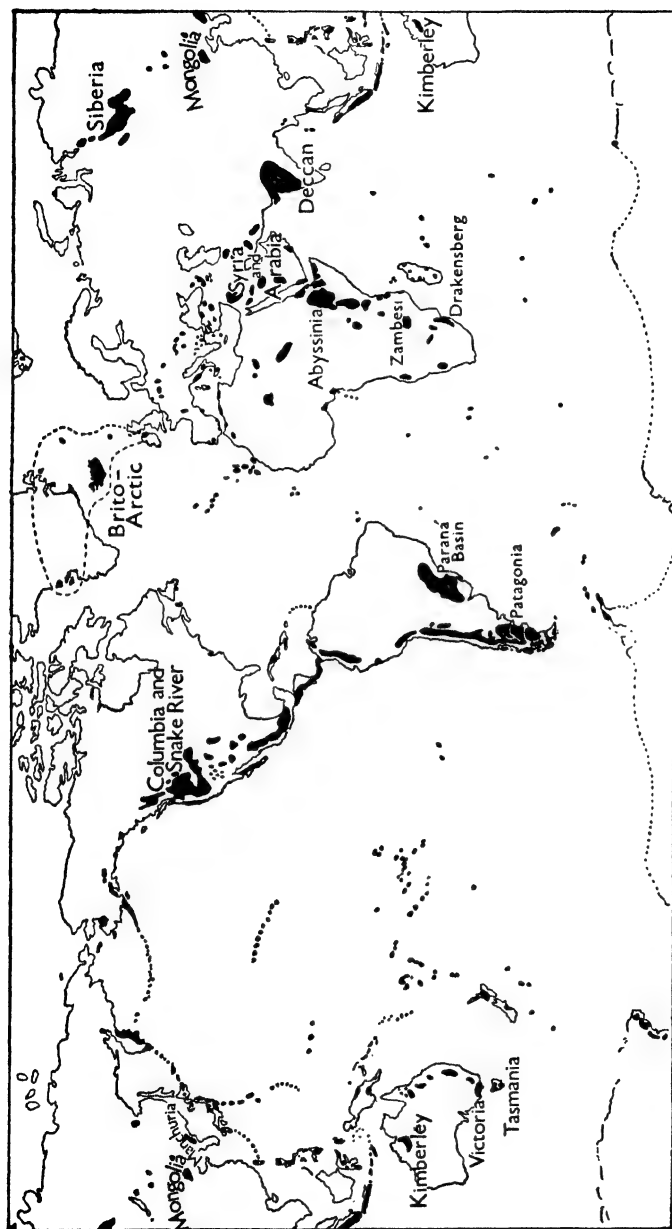



Fig. 252

Map showing the distribution of volcanoes (including many long extinct) and plateau basalts belonging to the latest geological cycle of activity. The ages of the plateau basalts (named on the map) are :

Early Jurassic : Siberia, Paraná Basin, Drakensberg, Zambesi, Tasmania. *Lower Tertiary :* Brito-Arctic, Deccan (India), Mongolia

Miocene to Recent : Patagonia, Columbia and Snake River, Victoria-Queensland, Kimberley, Abyssinia, Syria and Arabia, Iceland (still active)

vents). Figures are also given for the highly active belt of the Dutch East Indies, where the far eastern continuation of the Alpine-Himalayan orogenic belt faces the Indian Ocean. In two places the Pacific "girdle of fire" encroaches on the Atlantic: in the volcanic loop of the Lesser Antilles, and in the similar loop of the Southern Antilles, which links Patagonia with Grahamland. The association of volcanoes with coasts of Pacific type is clearly marked. In striking contrast, coasts of Atlantic type are relatively free, and along vast stretches entirely free, from volcanic activity.

A linear or arcuate arrangement of vents along the orogenic belts is highly characteristic, and is well illustrated in the Dutch East Indies (Fig. 211). Here and in similar arcs elsewhere (Fig. 213) the outermost zones, where earthquakes are frequent and mountain building is still in progress, show no signs of vulcanism. The volcanoes, whether active or extinct, are confined to parallel zones situated a hundred miles or more on the concave side of the zones of present-day tectonic activity. The vents are commonly strung out along lines of fracture in belts that were folded and uplifted during an earlier phase of the orogenic cycle now drawing to its close.

Along the Alpine-Himalayan orogenic belt—apart from the Dutch East Indies—volcanoes are distributed more sporadically. The volcanic zone can be traced from Madeira and the Canary Islands through the Mediterranean region (*e.g.* Vesuvius, Lipari Islands, Etna, and the Ægean volcanoes) to the Caucasus (Elburz), Armenia (Ararat), Persia (Demavend), and Baluchistan. Beyond the Himalayas the line continues through Yunnan and Burma to the Andamans and the little islands to the east, and so to the Dutch East Indies. The spacing is very uneven and there are long gaps, especially along the Himalayas and the Alps. It has been suggested that in such regions, where the crust has been intensely compressed by severe overfolding and overthrusting, the structure blocks the passageways which might otherwise have continued up to the surface, and so favours the injection of magma along the thrust planes rather than across them.

However this may be, it is clear that many of the European

volcanoes of the present cycle broke through the median areas within the branches of the orogenic belt (*e.g.* around the Tyrrhenian Sea ; along the Mediterranean coasts of Spain and North Africa ; and in the Hungarian basin), and also through the forelands outside (*e.g.* the volcanic districts of the Auvergne, the Eifel, and Bohemia). Further east, Tibet seems to be free from volcanoes, possibly because it stands too high ; only a few hot springs emerge. Active cones have been recorded from less lofty situations, however, near the rim of the Tarim basin in the very heart of Asia, and others are known in Mongolia and Manchuria. A noteworthy example of a Circum-Pacific median area with many recent vents and cones is the Colorado plateau (page 422).

Reference to the vulcanism associated with the African rift valleys has already been made on pp. 435 to 437. The only active volcano in West Africa is Cameroon Mountain, which forms part of a long volcanic chain that extends as a string of islands far into the Gulf of Guinea. Well-preserved cones and craters have recently been observed in the deserts of northern Africa, and there are many older volcanic piles among the highlands of the Sahara.

Several of the volcanic islands of the eastern Atlantic have already been mentioned, and to these must be added the Cape Verde group. Well within the ocean the islands that rise from the mid-Atlantic swell (*e.g.* the Azores, St. Helena, and Ascension) are all volcanic. Most of these are now extinct, but where the swell meets the ridge from Britain to Greenland there occurs one of the world's greatest lava fields—Iceland, with over a score of active volcanoes. Further to the northwest, just before the swell dies out, the most northerly of active volcanoes forms the island of Jan Mayen.

Besides Kerguelen, in the far south, the active volcanoes of the Indian ocean belong to the island groups of Comoro, Mauritius, and Réunion, all near Madagascar, which itself has many cones not long extinct. The scattered oceanic islands around Antarctica are also volcanic. On the fringe of Antarctica there are volcanoes bordering the Ross Sea, including the active cones of Erebus and Terror. The Pacific

has several groups and linear series of volcanic islands, while the innumerable coral islands point to the former existence of many more which have been worn down to submarine platforms, and are now capped with atolls. North of the Equator is the magnificently developed Hawaiian chain (p. 457). The Galapagos Islands lie across the Equator off the South American coast. South of the Equator there are the volcanic islands of Juan Fernandez (active) and Easter Island (extinct) in the east, and of Samoa in the west. Those to the west and south-west of Samoa (*e.g.* Fiji, Tonga, and Kermadec) belong to an outlying arc of the Circum-Pacific belt.

In the early days of geology, while the interiors of the continents still remained largely unexplored, it was not unnaturally assumed that all volcanoes occur near the sea. This apparent " rule " suggested the erroneous idea that sea water infiltrated into the magmatic reservoirs and so caused eruptions by being converted into steam. Such accidental steam explosions do occur, of course, but they are merely a superficial consequence of volcanic activity already there, and they are in no way to be regarded as its cause. The old generalization can no longer be justified, as the facts of distribution already outlined prove beyond dispute. Moreover, the distribution of the Jurassic and Tertiary plateau basalts (Fig. 252) shows that in the past widespread continental regions, most of which lay far from the seas and oceans of the time, were deluged with lavas on a prodigious scale.

Volcanic activity everywhere takes full advantage of profound fracturing of the crust, and since the greatest crustal deformations occur in the orogenic belts surrounding the continents (Figs. 209 and 210), it is hardly surprising that there should now be many volcanoes near the oceans. What is a matter for surprise is that there are not more volcanoes associated with the fractures responsible for coasts of Atlantic types. Obviously fracturing is not a sufficient condition for vulcanism. The essential condition is that there should be magma in depth to be tapped or to force its way up through

openings of its own making. The real problem of vulcanism is that of the origin of magmas, and to this subject we now turn our attention.

Speculations on the Causes of Vulcanism

Penetration of the earth's crust by bore-holes and mines shows that the temperature increases with depth. The rate of increase, or, in other words, the *temperature gradient*, varies considerably from place to place. Away from active volcanic centres the average gradient is about 30° C. per km., but in Ontario and the Transvaal it falls to as little as 9° or 10° per km. If the downward rate of increase continued uniformly, temperatures of fusion, say about 1050° C., would be

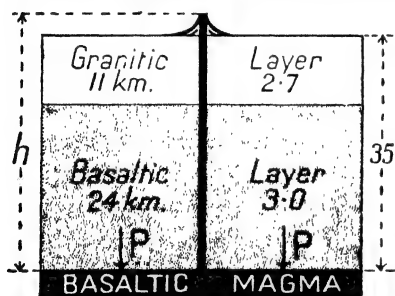



Fig. 253

Diagram to illustrate the ascent of basaltic magma through a fissure, as a result of crustal pressure (P) acting on a molten mass near the base of the basaltic layer. The densities of the rocks of the granitic and basaltic layers are taken as 2·7 and 3·0 respectively

reached in "average" regions at a depth of about 35 km. For this reason it was formerly thought that underlying the solid crust there was a world-wide layer of magma. As a result of high pressure such magma would be extremely stiff, and probably more like a glass than a mobile fluid, but nevertheless it would be capable of flow, and it would at once become eruptible if it were tapped by a fissure leading up to the surface.

If the lower part of the basaltic layer were actually in a state of fusion, it is easy to see that the magma could be driven to the surface, and even to the summits of lofty volcanoes, by the head of pressure due to the weight of the overlying rocks. Taking the average crust illustrated in Fig. 253 as an example, the pressure exerted by the rocks on a thin layer of basaltic

magma would be proportional to $11 \times 2{\cdot}7$ ($= 29{\cdot}7$ due to the granitic layer) plus 24×3 ($= 72$ due to the basaltic layer), making a total of 101·7. Let h be the limiting height to which the magma could be forced through a fissure feeding into the pipe of a volcanic cone. Since the density of molten basalt is about 2·7, we have

$$2{\cdot}7h = 101{\cdot}7\ ;\ \text{whence}\ h = 37{\cdot}67\ \text{km.} = 35 + 2{\cdot}67\ \text{km.}$$

Thus, not only would the magma reach the surface, but it could build up a cone and rise within the crater to a height of 2·67 km. or 9,750 feet. This is comparable with the highest of continental basaltic volcanoes. Etna, with a crater rim reaching an elevation of 10,739 feet, has probably reached the limit, for most of its eruptions are now confined to vents that have opened on the slopes below the rim. It should, of course, not be overlooked that the gases and vapours which are present in natural magma lower its specific gravity (as compared with that of artificially fused basalt), and so help its ascent, especially in the vicinity of the surface, where the concentrating gases may eventually burst out with explosive violence.

The existence of active basaltic volcanoes and of vast spreads of plateau basalts proves that, locally and at certain times, adequate supplies of basaltic magma must be available in the depths. The old idea that there is a world-wide eruptible layer of basalt can, however, no longer be sustained. As we shall see presently, the downward increase of temperature falls off in depth, and the basaltic layer is normally at a level far above the depth at which it could exist in a molten state. Moreover, if there were such a molten layer, a fissure eruption of plateau basalt, once started, should continue without interruption until all the eruptible material had either reached the surface or formed dykes and sills on the way up. Actually, we find that each of the great basaltic plateaus is made up of a large number of separate lava flows, and that there was a long interval of quiescence after each flow, during which its top was weathered to soil or laterite, sometimes to a depth of many feet. It follows that the available supply of magma at any one time was limited and rapidly exhausted, and that

the source must have been replenished again and again. Theoretically, such replenishment might be brought about either by localized fusion of the crystalline rocks of the basaltic layer, or by the ascent of fresh supplies of basaltic magma from still greater depths.

In the light of our present knowledge the problem of the origin of basaltic magma has become extremely difficult, and, strictly speaking, it cannot be regarded as solved at all, except in a speculative way. The main trouble arises from the distribution of temperature in depth. In 1906 Lord Rayleigh detected the presence of minute quantities of the radioactive elements in common rocks from all parts of the world (p. 409). It was then realized that the rocks of the earth's crust, including basaltic lavas, contain within themselves an unfailing source of heat. At first it was thought that the heat generated by radioactive disintegration would be sufficient to ensure temperatures of fusion near the base of the basaltic layer. Volcanic activity was then interpreted as the means by which the molten material escaped to the surface, so allowing the steadily accumulating heat to be periodically dissipated. Even if the temperature at the base of the basaltic layer normally fell a little short of that required to bring about fusion, it might locally reach the fusion point in places where the crust was depressed and thickened, *e.g.* beneath geosynclines blanketed by heavy sedimentation, and still more in the deep roots underlying mountain ranges, where the radioactive crust becomes abnormally thick. However, it is no longer possible to account so easily for vulcanism. More recent investigations have shown (*a*) that the crustal layers are not so thick—and therefore the basal temperatures are not so high—as was then supposed; (*b*) that the actual flow of heat through the crust in non-volcanic regions is far less than it would be if fusion temperatures were reached anywhere near the base of the basaltic layer; and (*c*) that in the roots of orogenic belts the time required for temperatures to rise to the fusion point would be well over a hundred million years, which means that the igneous activity contemporaneous with mountain building must have some other cause.

In assessing the downward increase of temperature we have to take into consideration not only the temperature gradient observed near the surface, but also the thermal conductivity of the crustal rocks and the quantity of heat generated within those rocks by the radioactive elements. The following simplified treatment of this problem gives an approximate

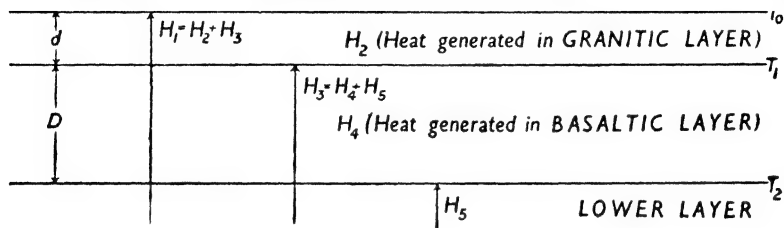



FIG. 254

Diagram to illustrate the heat flow through the earth's continental crust (away from volcanic areas), with data for calculating the downward distribution of temperature (see text)

Upper or Granitic Layer

T_0 = temperature of ground at surface (about 10° C.)
T_1 = temperature at base of granitic layer (to be calculated)
d = thickness of granitic layer (11 km. = 11×10^5 cm.)
k = thermal conductivity of granitic rocks (·0068 *c.g.s.* units)
H_1 = heat flow escaping at surface ($1{\cdot}3 \times 10^{-6}$ *cals/sec./sq. cm.*)
H_2 = heat flow from the radioactive elements in the granitic layer ($\cdot 33 \times 10^{-6}$ *c.g.s.* units)
H_3 = heat flow entering from beneath ($= H_1 - H_2 = \cdot 97 \times 10^{-6}$ *c.g.s.* units)

Intermediate or Basaltic Layer

T_2 = temperature at base of basaltic layer (to be calculated)
D = thickness of basaltic layer (24 km. = 24×10^5 cm.)
K = thermal conductivity of basaltic rocks (·004 *c.g.s.* units)
H_4 = heat flow from the radioactive elements in the basaltic layer ($\cdot 65 \times 10^{-6}$ *c.g.s.* units)
H_5 = heat flow entering from beneath ($= H_3 - H_4 = \cdot 32 \times 10^{-6}$ *c.g.s.* units)

solution, using the data summarized under Fig. 254. It should be explained that the heat flow at the surface is given by the product of the temperature gradient by the thermal conductivity of the rocks through which the heat flows, both of which factors can be accurately measured. It is found that the heat flow in different places varies much less than the corresponding temperature gradients. In Britain, for example, it ranges between $2{\cdot}07 \times 10^{-6}$ calories per second

per sq. cm. near Glasgow (where the influence of the Mull swarm of dykes makes itself felt—*cf.* Fig. 38), and 1·1, in the same units, around London (where there was no Tertiary igneous activity, and probably none for many hundreds of millions of years). In South Africa the average heat flow is 1·16, and in Michigan about 1·0. The average heat flow in non-volcanic regions appears to be about 1·3 in the units stated.

The heat flow H_1 from the granitic layer is the sum of H_2, which is the heat generated by the radioactive elements in the layer, and H_3, which is the heat that enters from below. The average heat flow is $(H_1 + H_3)/2$; and the average temperature gradient is $(T_1 - T_0)/d$.

Hence, we have $\dfrac{H_1 + H_3}{2} = \dfrac{k(T_1 - T_0)}{d}$

$$\text{whence} \quad T_1 = T_0 + \frac{d}{k}\left(\frac{H_1 + H_3}{2}\right).$$

From the data listed under Fig. 261,

$$T_1 = 10° + \frac{11 \times 10^5}{\cdot 0068}\left(\frac{1\cdot 3 + \cdot 33}{2}\right) \times 10^{-6} = 195°\ \text{C}.$$

Similarly, the heat flow H_3 from the basaltic layer is the sum of H_4, which is generated within the rocks of the basaltic layer, and H_5, which is the heat that enters from below. The average heat flow is $(H_3 + H_5)/2$; and the average temperature gradient is $(T_2 - T_1)/D$.

As before, $\dfrac{H_3 + H_5}{2} = \dfrac{K(T_2 - T_1)}{D}$

$$\text{whence,} \quad T_2 = T_1 + \frac{D}{K}\left(\frac{H_3 + H_5}{2}\right)$$

$$= 195° + \frac{24 \times 10^5}{\cdot 004}\left(\frac{\cdot 97 + \cdot 32}{2}\right) \times 10^{-6} = 585°\ \text{C}.$$

The curve drawn through these values for T_1 and T_2 in Fig. 255 gives the approximate distribution of temperature

through the average crust. It will be seen that throughout the granitic and basaltic layers the temperatures are everywhere far below those required for magma formation. The gap amounts to hundreds of degrees. The data are naturally subject to variation from place to place, but, so far as we know at present, no permissible variations in the data adopted make it possible to bridge the gap. Yet the gap must sometimes be bridged to account for the local existence of basaltic magma, and still more for the local generation of granitic magma at no great depth beneath the surface. Evidently

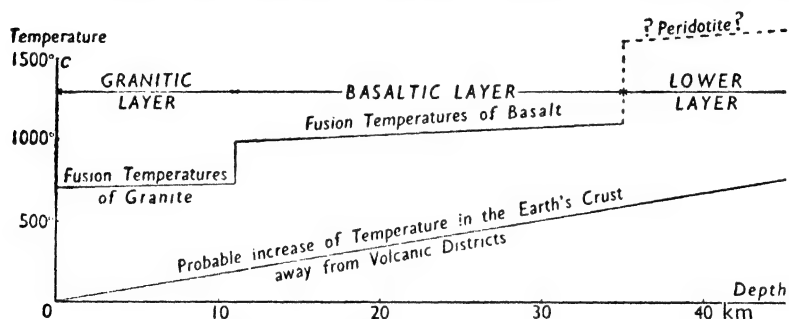



Fig. 255

Diagram showing the approximate downward increase of temperature in a non-volcanic continental region, together with the temperature required at each depth for the generation of magma from the rocks of the crustal layers

enormous quantities of heat somehow appear in the orogenic belts, and also beneath those parts of the more stable crust where plateau basalts have flooded the surface. How is it that these areas have become the temporary "hot spots" of the earth, while the rest of the crust was cooling? It is obvious that the continental crust does normally cool, for almost every part of it has been the site of igneous activity at some time or other during the earth's history. Throughout geological time the hot spots have shifted about from one set of localities to another, always accompanying the orogenic belts of the time, but also appearing more or less at random at various places in the intervening tracts.

From these considerations it appears that the local heating

up of the crust is to be ascribed to processes operating in the underlying substratum. And here we inevitably enter the uncertain realm of speculation where there are various hypothetical possibilities to be explored, but few guiding facts. One possibility is that magma generation may be a consequence of sub-crustal convection currents, and this is perhaps the most promising suggestion available at the moment.

It is conceivable that the base of the basaltic layer may become fused by heat carried up by hot ascending currents (*cf.* Fig. 215), but if such a process were at all important it would probably give rise to far more widespread conditions of crustal fusion than we have any right to assume. It is also conceivable that beneath the orogenic belts, where opposing currents meet and turn down, part of the basaltic layer may be dragged into the currents, as illustrated in Fig. 262 and described on p. 507. Such basaltic material would be intensely metamorphosed, and would ultimately become fused, wholly or selectively. The resulting magma, because of its relatively low specific gravity, would sooner or later ascend again. Part of it might be squeezed back into the higher levels of the orogenic belt, but much of it would probably reach the crust far from its original source, and so become responsible for basaltic eruptions on the continents and ocean floors. It should be noticed that although Fig. 262 is drawn to illustrate the case where magma ascends from beneath the ocean basins, the mechanism portrayed is just as likely to bring basaltic magma to continental areas.

The most conspicuously hot regions of the crust are undoubtedly the orogenic belts, and this may seem at first sight to be inconsistent with the hypothesis that these are also the regions where the convection currents begin to descend. Sinking currents cannot be so hot as rising currents. But there are good reasons for supposing that the crust overlying the zone where two opposing currents approach and turn down must inevitably become abnormally hot.

In the first place, the down-dragging of the crust and of the upper crystalline part of the substratum, during the development of a geosyncline and subsequently during root

[*Am. Mus. Nat. History, N.Y.*

Crater Lake, Oregon. A vast caldera, with the cone of Wizard Island rising above the lake

[*E.N.A.*

(A) Hex River Valley, Cape Province, South Africa, showing the north-west pre-Devonian orogenic belt (middle and foreground) approaching the east to west Cape Foldings (background)

[*C. T. Trechmann*

(B) Erratic block in Dywka Tillite (late Carboniferous) resting on a glaciated rock surface, Nooitgedacht, near Kimberley, South Africa

formation, must involve intense shearing and friction, and therefore the liberation of a great deal of heat. The observation that certain thin bands of mylonite (p. 80) show obvious signs of having been fused proves that the heat due to friction is by no means negligible. Although it is doubtful whether such heat can be produced sufficiently rapidly to promote fusion on any considerable scale by itself, it must nevertheless be taken into account as an important contributory factor.

In the second place, when rocks are intensely sheared certain constituents are liberated in a mobile state, so that they become free to migrate towards places of lower pressure. This process must operate within the mountain roots, and it may become even more important in rocks dragged down into the underlying currents, until it merges into true fusion, as a result of the steadily increasing temperature. If basaltic rocks are drawn into the descending currents they will gradually be heated up by their surroundings, and blebs and streaks of magma will be generated as the latent heat of fusion is supplied. Such magma, and indeed all the mobile constituents, whether liberated by shearing or heat, or both, will be squeezed back towards the crust, just as water is squeezed out of a wet blanket as it is passed through the rollers of a mangle. The descending currents must operate like a mangle towards all the materials within them down to very great depths, and consequently there should be an upward streaming of intensely heated mobile materials, rich in gases and volatile emanations, all migrating towards regions of lower pressure—that is, towards the surface.

Eventually most of these materials will pass into the orogenic belt, partly as magmas, and partly as a procession of highly energized and chemically active emanations. As the latter saturate the rocks (rocks already heated by friction) the cycle of metamorphism summarized in Fig. 21 reaches its culmination and new magmas are formed within the crust itself. From the testimony of the rocks now exposed in the heart of ancient orogenic belts, it has been inferred that granite magma can actually be generated in this way (p. 65). A hypothetical source for the granite-making emanations has

now been traced, but it must be clearly understood that the process envisaged in the above discussion is at present no more than a plausible hypothesis designed to account for a few of the more obdurate facts concerned with the puzzling behaviour of our planet.

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Chapter XXI

CONTINENTAL DRIFT

Continental and Oceanic Relationships

The continents are essentially thin slabs of sial, distributed to form a northern pair, known together as Laurasia, and a more scattered southern group, collectively referred to as Gondwanaland. The outer peripheries of the members of each group are defined by the orogenic belts of the last great tectonic revolution (Figs. 209 and 210), and the coast-lines, generally backed by mountains, are of Pacific type (p. 401). The inner margins of the members of each group, against the Arctic, Atlantic, and Indian oceans, are fractured and in many places downfaulted towards the sea, and the coast-lines are of Atlantic type (p. 400). Across the floors of these intervening oceans the sial layer, where present at all, is patchy in distribution and very much thinner than in the bordering continents. Much of the Pacific floor, however, lacks a layer of sial altogether. The major structural units of the face of the earth thus fall naturally into the following pattern :

1a The continents of the *Laurasia* group
  1b The intervening North Atlantic and Arctic oceans
2a The continents of the *Gondwanaland* group
  2b The intervening South Atlantic and Indian oceans
  3 The oceanic basin of the *Pacific*, everywhere outside **1** and 2 (see Fig. 208)

To what extent these primary units and their arrangement have been stable or otherwise during geological time is one of the fundamental problems of geology. For nearly a century this question has been vigorously debated as one line of evidence after another has been discovered and followed up. Before then the widespread occurrence of marine sediments over the lands suggested that the continents could sink to oceanic

depths and the ocean floors rise to become dry land. It was gradually recognized, however, that these deposits merely prove flooding of the lands by shallow seas ; they do not demonstrate interchange of continent and ocean. For this reason, amongst others, Dana expressed the view in 1846 that continents and oceans have never changed places, and that the general framework of the earth has remained essentially stable. Nevertheless, Edward Forbes, tackling the subject from the biological side in the same year, found it impossible to explain how animals and plants had migrated from one continent to another unless some parts of the oceans had formerly been land. Thus began the long controversy regarding the permanence of the continents and ocean basins.

Support for permanency is found in the fact that deep-sea deposits like those now forming on the ocean floors are confined to one or two marginal islands (p. 320) and are consistently absent from the strata now exposed on the continents proper. Moreover, from the standpoint of isostasy it is very difficult to picture a process which could bring about widespread changes of level amounting to two miles or more. The explanation given for the subsidence of geosynclines and the uplift of orogenic belts can hardly be applied to areas of continental extent. But since the continents themselves are vast complexes of orogenic belts of different ages, it is obvious that they must have been profoundly modified during geological time, and that a good deal of variation in extent and position must therefore be conceded.

The extreme advocates of permanency have also had to yield ground in face of the evidence that certain regions that were undoubtedly land long ago are now parts of the Atlantic and Indian oceans. In Britain the sediments of the Torridonian and some of those of the Old Red Sandstone and Carboniferous were derived from a land that lay to the north and west of Scotland. On the other side of the Atlantic the Appalachian geosyncline was largely filled with sediment from the south east. The gold-bearing conglomerates of the Gold Coast were carried there by a great river that drained a land lying to the

south. In each of these cases the site of the ancient land is now open ocean.

What, then, has happened to these vanished lands? Theoretically there are three possibilities ·

(*a*) They may have subsided bodily to great depths, while retaining their original positions on the earth's surface. This is the apparently obvious answer, but it raises a serious isostatic difficulty. If a tabular iceberg split into two, the separated bergs might slowly drift apart, but neither could sink. This analogy has a value in introducing the idea of continental drift as an alternative to continental sinking.

(*b*) Bodily horizontal displacement may have occurred. If this happened there would be no subsidence. Labrador might be the land that formerly lay adjacent to Scotland. The gold-bearing tracts of the Guianas and Brazil might be the source of the gold deposits of the Gold Coast.

(*c*) More probably, however, the crustal layers, including the sial, may have been stretched out horizontally between the displaced continents, the sial thereby becoming thin and patchy. In this case the resulting isostatic readjustment would involve sinking. The known structure of the Atlantic and Indian ocean floors is consistent with this explanation.

For many years it was naturally assumed without question that if interchanges between continent and ocean had to be postulated the movements involved could not be other than vertical. The suggestion that there might have been lateral displacements of the continental masses on a gigantic scale is generally ascribed to F. B. Taylor in America (1908) and to Alfred Wegener in Germany (1910). For several years these pioneers developed their unorthodox hypotheses quite independently. Actually, however, the same idea had occurred to Antonio Snider more than fifty years before. In a book with the optimistic title *La Création et ses Mystères dévoilés* (Paris, 1858) he published the two maps here reproduced as Fig. 256. Snider's reconstruction of Carboniferous geography was intended to explain the fact that most of the fossil plants
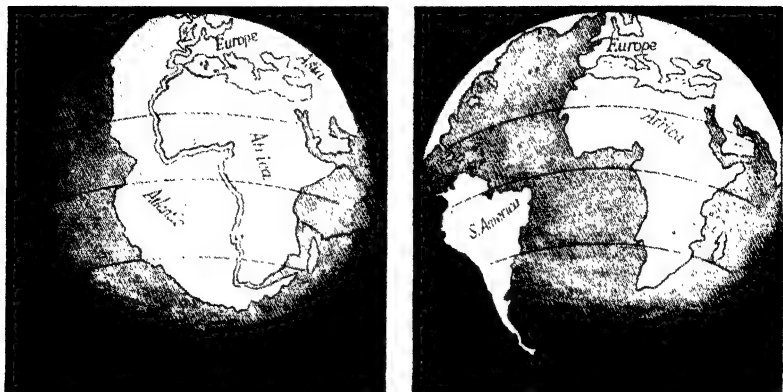
Fig. 256

Maps published by A. Snider in 1858 to illustrate his conception of continental drift. The left-hand map represents the supposed coalescence of the continents in late Carboniferous times

preserved in the Coal Measures of Europe are identical with those of the North American Coal Measures. Although the two diagrams reappeared in J. H. Pepper's highly entertaining *Playbook of Metals* (London, 1861), the idea they embodied was evidently regarded as too fantastic and outrageous to be worthy of attention. Not unnaturally it soon became completely forgotten.

Taylor's Hypothesis of Continental Drift

It was not until Wegener published his famous book on the subject in 1915 that the possibility of continental drift began to receive serious attention. But Taylor must be given credit for making an independent and slightly earlier start in this precarious field. His immediate object was to account for the distribution of mountain ranges. He pictured the original Laurasia as being a continuous sheet of sial and supposed it to have spread outwards towards the Equator, more or less radially from the Polar regions, much as a continental ice sheet would do. Wherever the resistance was least the crust flowed out in lobes, raising up mountainous loops and

arcs in front (*cf.* Fig. 209). Such movements, of course, would be impossible without complementary stretching and splitting in the rear. And, indeed, there is ample evidence of down-faulting and disruption in the coastal lands and islands of the Arctic and North Atlantic, and especially in the highly fractured region between Greenland and Canada, the map of which looks like a jig-saw puzzle with the separate bits dragged apart. In the Southern Hemisphere the originally continuous Gondwanaland similarly spread out, breaking up into immense rafts which also migrated towards the Equator and raised up mountains in front (Fig. 210). The basins of the South Atlantic and Indian oceans are interpreted as the stretched and broken regions left behind or between these drifting continents.

For two reasons Taylor's hypothesis received scant attention. As we have already seen (p. 384), a certain amount of lateral continental movement is implied by the structures of orogenic belts, but it seemed to be unnecessarily extravagant to invoke thousands of miles of horizontal displacement when from twenty to forty—rarely more—would suffice. Secondly, Taylor's attempt to explain the alleged movements was quite unacceptable. He postulated that the moon first became the earth's satellite during the Cretaceous, and that at the time of its close approach and capture it was very much nearer to the earth than it is to-day. The resulting tidal forces were supposed to be sufficiently powerful not only to alter the rate of the earth's rotation, but also to drag the continents away from the poles.

Apart from the improbability that the earth was without a moon before the Cretaceous, there are two fatal objections to this hypothesis :

(*a*) If the late Cretaceous and Tertiary mountain building is to be correlated with the supposed capture of the moon, then we are obviously left with no explanation for all the earlier orogenic cycles.

(*b*) If the tidal force applied to the earth by the newly captured moon had been sufficient to displace continents and

raise mountains on the scale required, then, as Jeffreys has shown, the friction involved would have acted like a gigantic brake and the earth's rotation would have been brought to a standstill within a year.

Taylor's " explanation " is completely untenable, but from the criticisms one very important conclusion may be drawn. The fact that the earth continues to rotate shows that neither tidal friction nor any other force applied from outside the earth can be responsible for mountain building or for continental drift, if it occurs. We have already found a cause for mountain building inside the earth, and if a cause for continental drift be also required, it too must be looked for within the earth.

Wegener's Hypothesis of Continental Drift

Wegener's highly complex conception of the evolution of the continents is graphically illustrated by his own strange, but now familiar, maps (Fig. 257). His picture of the world in Carboniferous times is strikingly similar to Snider's, except that India and Antarctica are tucked in between Australia and Africa, with the horn of South America forming an outer wrapping. For this compressed combination of Laurasia and Gondwanaland he proposed the name *Pangæa*. In one important respect, however, neither Wegener's Carboniferous map nor Snider's gives adequate expression to its author's ideas. Snider urged that the forests of the Coal Measures were tropical, and that in consequence Europe and North America must have been near the Equator. This implies that South Africa must have been near the South Pole. Conversely, Wegener inferred that the Carboniferous South Pole occupied a position just off the present South African coast (Fig. 260). His scheme thus involves not only continental drift, but also extensive wandering of the poles.

The present distribution of the continents is regarded as a result of fragmentation by rifting, followed by a drifting apart of the individual masses. The southern continents began to unfold during the Mesozoic era by being dragged away from
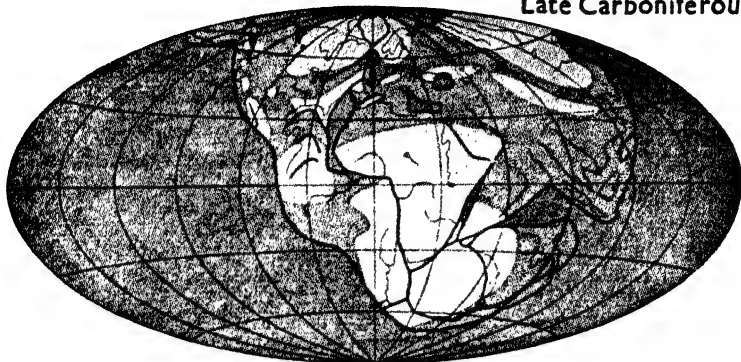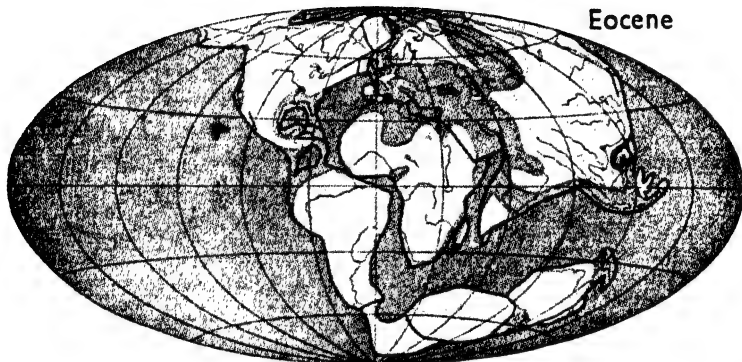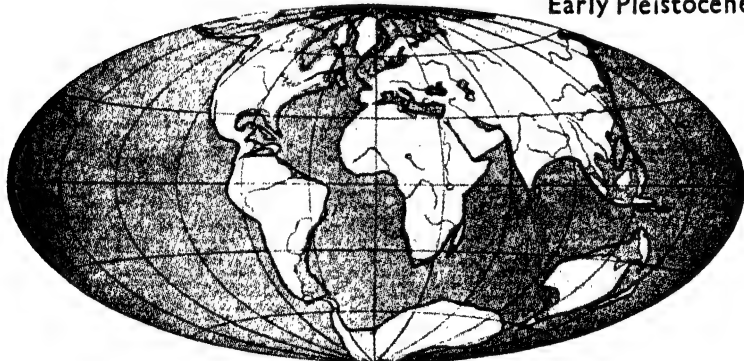
Fig. 257

Wegener's reconstructions of the distribution of the continents at three periods, to illustrate his hypothesis of continental drift. Africa is shown in its present-day position merely as a centre of reference. Shaded continental areas represent shallow seas. (From A. Wegener, *Die Entstehung der Kontinente und Ozeane*, 1915)

wherever the South Pole happened to be at any given time during the progress of the outward movements. Somewhat later North America began to break loose and to drift away to the west, Greenland being the last to go. The Atlantic is the immense gap left astern, filled up to the appropriate level by sima from below. A peculiarity of Wegener's interpretation is his insistence that the opening of the North Atlantic was accomplished almost entirely during the Pleistocene. By the time the poles had reached their present positions Antarctica found itself stranded over the South Pole ; Africa lay athwart the Equator ; India had been tightly wedged into Asia, where its originally northern part now lies buried under the high plateau of Tibet ; and Australia had advanced far into the Pacific, by-passing the Banda arc and coming to rest against its eastern end.

The drift of the continents away from the poles was dramatically described by Wegener as the *Polflucht*—the Flight from the Poles. He ascribed it to the gravitational attraction exerted by the earth's equatorial bulge. The force is a real one but, unfortunately for Wegener, it would require a force many millions of times more powerful than this to drag the continents from their moorings.

Wegener also postulated a general drift towards the west. As the Americas moved westwards against the resistance of the Pacific floor, their prows were crumpled up into great mountain ranges. Between the two immense rafts a trail of fragments lagged behind and formed the islands of the West Indies. The stretched-out isthmus connecting South America and Antarctica similarly lagged behind, forming the horns of the two continents and shedding bits of sial that now remain as the island loop of the Southern Antilles. The alleged effects of the westerly drift of Asia are less happily conceived. The great oceanic deeps are supposed to represent gaping fissures torn in the Pacific floor and not yet fully healed, while the island festoons are strips of sial that partially lost their attachment to the mainland.

The westward movements are ascribed to the differential attractions of the moon and the sun on the continents. Tidal

friction acts like a brake on the rotating earth, and as the effect on protuberances is greater than than that on lower levels of the crust the continents tend to lag behind. If they did lag behind, they would appear to drift to the west. But here again the force invoked is hopelessly inadequate to overcome the enormous resistance that opposes actual movement. The tidal force barely affects the earth's rotation, and is actually ten thousand million times too small to move continents and raise up mountains.

In support of his presentation of the case for continental drift Wegener marshalled an imposing collection of facts and opinions. Some of his evidence was undeniably cogent, but so much of his advocacy was based on speculation and special pleading that it raised a storm of adverse criticism. Most geologists, moreover, were reluctant to admit the possibility of continental drift, because no recognized natural process seemed to have the remotest chance of bringing it about. Polar wandering, the " flight from the poles," and the westerly tidal drift have all been discarded as operative factors. Nevertheless, the really important point is not so much to disprove Wegener's particular views as to decide from the relevant evidence whether or not continental drift is a genuine variety of earth movement. Explanations may safely be left until we know with greater confidence what it is that needs to be explained. Let us, then, turn to the evidence with an unbiased mind.

The chief criteria for continental drift are based on the following considerations :

(*a*) If two continents, now far apart, were originally united, it should be possible to detect the fact by the recognition of certain features that were shared in common by the separated lands, *e.g.* orogenic belts of which the broken ends can be naturally joined up ; other details of geological history as revealed in the sedimentary sequences ; and the identity of the fossil remains of animals and plants (especially of land and freshwater species) which could migrate freely across the united continents but not across an intervening ocean.

(*b*) If the continents formerly occupied widely different positions on the earth's surface, then the distribution of climatic zones, as inferred from geological evidence, should have correspondingly changed.

The Opposing Lands of the Atlantic

The parallelism of the opposing shores of the Atlantic has been a subject of discussion ever since Francis Bacon first drew attention to it in 1620. To Wegener it suggested that the Atlantic is an enormously widened rift with the sides still matching "as closely as the lines of a torn drawing would correspond if the pieces were placed in juxtaposition." The fit, even of the broken edges, is far from being as perfect as this, however. No significance can be attached to an argument based on a geographical pattern that is little more than a temporary accident. In Tertiary times the outlines of the coasts were very different from those of to-day. Nor is parallelism to be expected as a normal result of continental drift, for it is mechanically impossible that the sial blocks could have moved apart without a certain amount of rotation and a good deal of marginal distortion due to stretching and faulting. We know that there are patches of sial on the Atlantic floor, the two most notable being the long S-shaped swell that traverses the ocean floor from end to end, and the broad rise that links Greenland to Britain by way of Iceland and the Faroes. If all this intervening sial were closed up again, until it became a sheet of normal continental thickness, it would make a land many hundreds of miles wide. Consequently, if we imagine the Atlantic to be closed up, it is obvious that not only the present shores but also the edges of the continental shelves would be still separated by a distance of this order. Matching of the geological correspondences will clearly be much less precise than would be expected if the coast-lines dovetailed as perfectly as on Wegener's too closely fitting maps.

Nevertheless, the actual similarities are very remarkable. As illustrated by Fig. 258, the transverse orogenic belts all
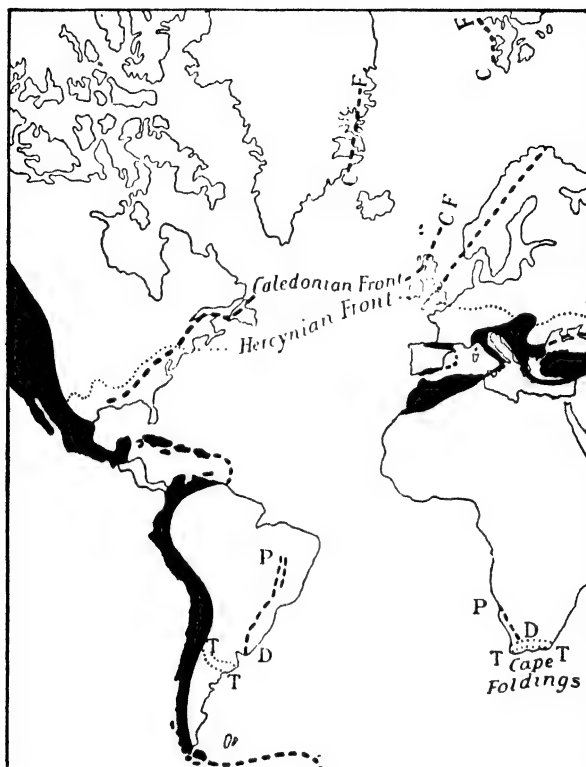
FIG. 258
Map to illustrate the tectonic correspondences on the opposing shores of the Atlantic

appear to match surprisingly well. The westward convergence of the Caledonian and Hercynian fronts towards Ireland is continued in North America, where the fronts finally cross. The " fit " is not altogether satisfactory, however, because the times of most intense folding in the Appalachians are not the same as in Europe. Nor is it quite certain that the two Caledonian fronts should be linked together as indicated. There is another stretch of Caledonian front along the eastern side of Greenland, precisely where it should be to fill the gap between the North-west Highlands and Spitzbergen. But it should be remembered that the Iceland ridge stands badly in

the way of a former close-up, and it must not be overlooked that the Greenland front may have been directly connected with the loose end of Newfoundland. The British Caledonian belt might then join up with a Caledonian belt known to traverse the Sahara. This particular problem cannot be settled until the geology of Greenland and the Sahara are better known.

It is improbable that the Tertiary orogenic belts that strike out into the Atlantic were ever adjacent, as they represent earth movements that occurred when continental drift (assuming it for the moment) was already well advanced. Farther south, however, there are converging Pre-Devonian and Triassic orogenic belts in South America which can be matched in South Africa. Here again, the crossing foreshadowed near the River Plate is accomplished behind Cape Town (Plate 95A). The distinguished South African geologist, du Toit, has suggested that the Cape Folds are part of the same orogenic belt as that of eastern Australia (Fig. 261).

For many years du Toit has been indefatigable in assembling the evidence bearing on continental drift. In his well-known book *Our Wandering Continents* he shows that a striking series of correspondences can be recognized in the sediments, fossils, climates, earth movements, and igneous intrusions of the two sides of the Atlantic. Both had essentially the same geological history during Palaeozoic and early Mesozoic times, and the combined evidence points very persuasively to the high probability that they were then very much closer together than now. Du Toit considers it possible that the original distance between the present opposing shores may have been as little as 250 miles. But this is a minimum estimate and not perhaps the most probable.

The chief adverse argument is a palaeontological one. Columns A and B of the adjoining table indicate the degree of resemblance found between land animals that are free to migrate from one part of a continuous continent to another. C indicates the actual resemblance so far found between the known fossil remains of South African and South American Triassic reptiles. A possible reason for the obvious discrepancy

	A	B	C
Families . .	100	89	43
Genera . . .	82	64	8
Species . . .	65	26	0

A Percentage of recent Ohio mammals also occurring in Nebraska, 500 miles away
B Percentage of recent French mammals also occurring in northern China, 5,000 miles away
C Percentage of known South American Triassic reptiles also found in the Triassic of South Africa, now 4,750 miles apart

is that the proportion of individual land animals preserved as fossils is so minute that the chances of finding fossils of the same genus in widely separated localities are slight, and of identical species very remote. Negative evidence may be destroyed at any moment by fresh discoveries, whereas genuine positive evidence can never be explained away. And positive evidence is by no means lacking. Near the top of the Carboniferous in both South Africa and South America there is a thin band of deltaic clay containing the bones of a small freshwater reptile called *Mesosaurus*. The little animal has been found nowhere else in the world. The region between the ancient deltas in which he lived must have been drained by rivers, and it was therefore occupied by land. The choice evidently lies between accepting continental drift or postulating a giant land bridge across what is now 4,000 miles of ocean. Here the late Carboniferous glaciation of Gondwanaland helps us in making a decision.

The Climatic Zones of the Late Carboniferous

Beds of *tillite* (consolidated till or boulder clay), now known to be of late Carboniferous age, were first recognised in tropical India in 1857, in South Australia in 1859, in South Africa in 1870, and in Brazil in 1888. As these amazing discoveries were followed up it became unmistakably clear that Gondwanaland had been glaciated on a gigantic scale at a time when Laurasia enjoyed mild or tropical climates.

The widespread Dwyka tillite of South Africa has been

partly obliterated by erosion, and is partly hidden by later formations. But innumerable exposures still occur at intervals from the Transvaal towards the Cape and from South-West Africa to Natal. In many places it can be seen resting on a glaciated floor, characteristically scored with striations. *Roches moutonnées*, excavated rock basins, drumlins, and varved clays have been discovered. The tillite itself contains grooved and ice-faceted boulders and erratic blocks (Plate 95B), some of which have been transported for hundreds of miles from the north. In some localities two or three tillites are known, with intervening interglacial deposits, showing that, as in the Pleistocene ice ages, there was more than one major advance and retreat of the ice. The successive glaciations were not all from the same centre, but migrated from west to east. The associated deposits show that the glaciated region was one of moderate relief, and for the most part low-lying. At the margins the ice terminated in shallow water, marine, brackish, or fresh, which followed up the ice as it retreated. No high mountain range or plateau lay to the north, from which great valley glaciers might have descended. The glaciation was the work of a continental ice sheet that spread outwards under the pressure of its own great thickness.

The ice came from centres lying far to the north, and in the latest of the glaciations from beyond Natal, outside the present continent. Since it must have radiated not only towards the south, but outwards in all directions, it follows that the Dwyka tillites should be only part of a once continuous ring of such deposits, surrounding the region of ice dispersal. Confirming this deduction tillites of the same age have been found in the north of Angola, in the eastern Congo, in Uganda, and in Madagascar, and in the first three of these territories it has been established that the ice moved from the south. As indicated in Fig. 259, the ice sheet advanced beyond the Equator.

In India, far to the north of the Equator, similar evidence has been found in Orissa and the Central Provinces, and still farther north in the Punjab. The Himalayas did not then exist, nor did any other mountain range from which the ice might have spread over the plains. Here again we see only a

segment of a great ice sheet, a part in which the ice radiated northwards, away from the present Equator. Four of the Australian States, together with Tasmania, were also glaciated from what is now the south. In addition to the equivalents of the Dwyka tillites there is evidence in Australia of an earlier glaciation about the middle of the Carboniferous, and of a later one in the Permian, both of which were also experienced in South America. The tillites of Dwyka age, however, are those best represented in South America, where the ice advanced from what is now the Atlantic over parts of Brazil, Uruguay, and Argentina, and the whole of the Falkland
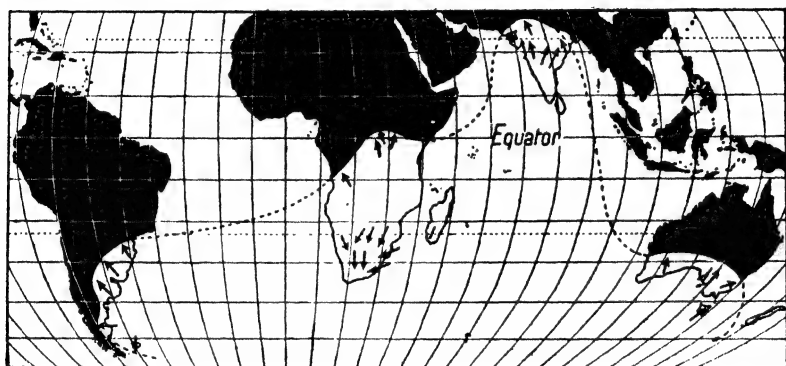
Fig. 259
Map showing the distribution of the late-Carboniferous glaciation of Gondwanaland. The arrows indicate the directions of ice movement

Islands. Of all the fragments of Gondwanaland the only one that has failed to furnish evidence of the late Carboniferous glaciation is Antarctica. As most of Antarctica is at present shrouded by ice, this is not a matter for surprise.

A glance at Fig. 259 shows that the glaciated lands now occupy a considerable area of the tropics on both sides of the Equator. With the continents in their present positions such a distribution of ice-sheets is hopelessly inexplicable. The suggestion that Gondwanaland rose from sea level to a plateau so enormously high that it was above the snow line is negatived by ample evidence that it was nowhere very high. But whether it was or not, the tropics could not have been glaciated down

to sea level without the development of still greater ice sheets over the northern lands. The only evidence of Carboniferous glaciation in the north is found in Alaska, which has probably never been far from the North Pole, and near Boston, in the Appalachian orogenic belt, which at that time may well have been a high mountain range. On the other hand the great Carboniferous coal forests were flourishing from North America
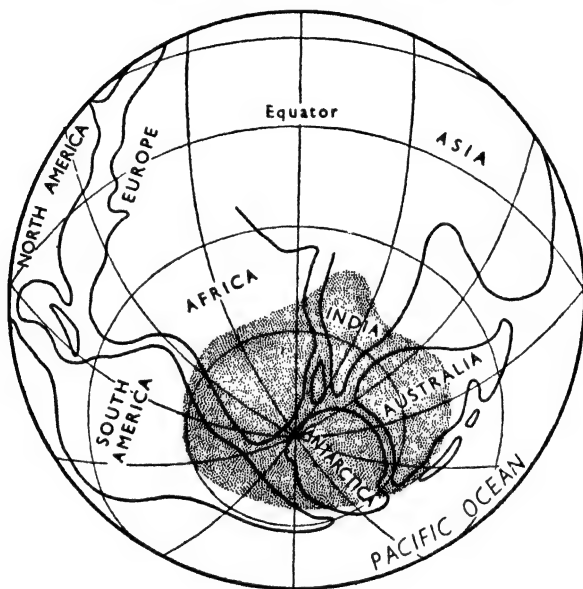
FIG. 260

Map showing the distribution of the late-Carboniferous glaciation of Gondwanaland, with the continents reassembled, though not so closely, as interpreted by Wegener

to China while Gondwanaland lay under ice. Moreover, deposits of laterite and bauxite that could only have formed in a tropical climate are found in the Upper Carboniferous of the United States (Kentucky and Ohio), Scotland (Ayrshire), Germany, Russia (south of the Moscow basin), and China (Shantung). The inference that the equatorial zone of the time is roughly indicated by this lateritic belt is irresistible.

No amount of polar wandering, even if it could be admitted, would give a distribution of climatic girdles around the globe corresponding to the picture outlined above. Wherever the South Pole is imagined to have been in order to account for any one of the glaciated regions, it would still have been too distant from the others to account for more than one of them. The problem, indeed, remains an insoluble enigma, unless the straightforward inference is accepted that all the continents except Antarctica lay well to the south of their present positions,
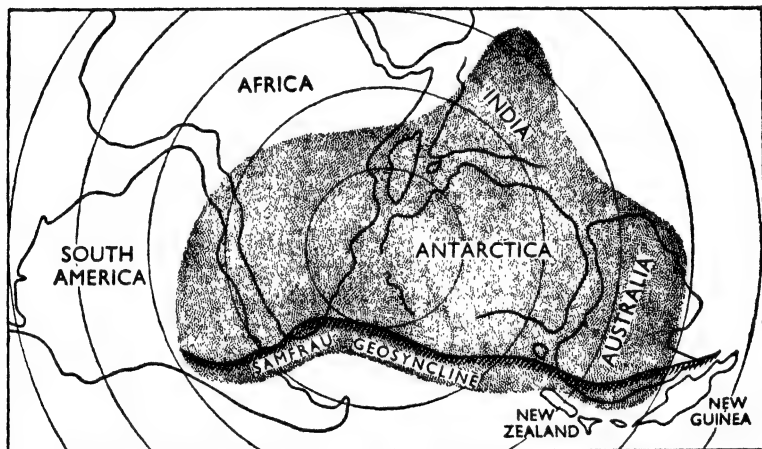
Fig. 261

Map showing the distribution of the late-Carboniferous glaciation of Gondwanaland, with the continents reassembled according to du Toit's interpretation

and that the southern continents were grouped together around the South Pole. In attempting a circumpolar reassembly the position to be allotted to Antarctica is necessarily uncertain. Wegener places it between Australia and South America (Fig. 260) ; whereas du Toit, guided by meagre stratigraphical and tectonic clues, thinks it may have been between Australia and Africa (Fig. 261). With either arrangement the ice sheets all fall within an area comparable with that glaciated in the Northern Hemisphere during the Pleistocene. Moreover, as indicated in Fig. 260, the lateritic belt then comes into line with the Equator of the time, and other known details

of the Carboniferous climatic girdles also fall consistently into their appropriate places. The site of the Hawaiian Islands would have been approximately over the North Pole at this time. Consequently, no evidence of a North Polar ice cap is to be expected. The nearest of the present land areas where signs of glaciation might reasonably be looked for are California and Alaska. The Carboniferous rocks of California are marine sediments, where again no evidence could be expected. But in Alaska a late Carboniferous tillite occurs, just where it ought to be.

The only serious argument advanced against the validity of the above solution is that it merely exchanges one embarrassing problem for another—the difficulty of explaining how continental drift on so stupendous a scale could have been brought about. By itself this consideration might be a reason for sitting on the fence, but the real antithesis is not so simple. If one rejects continental drift and accepts the possibility that Central Africa could have been glaciated while Britain had a tropical climate, one must also admit the necessity for land bridges, which have since subsided to oceanic depths. The continental drift solution has the advantage that it reduces two baffling problems to one, while at the same time it removes many other less intractable difficulties.

Before leaving the subject of climates, it is of interest to notice that South Africa was glaciated several times before the Carboniferous. A widely distributed tillite occurs in strata of Lower Devonian age in the Cape Province. In the late Pre-Cambrian, glaciation occurred on a scale comparable with that of the late Carboniferous—the regions affected including the Transvaal, Rhodesia, the Congo, Angola, and South-West Africa. Still earlier in the Pre-Cambrian yet another tillite is preserved in the Transvaal, and farther back still South-West Africa provides evidence of what may be one of the earliest glaciations known. It thus appears that for at least 1,000 million years the position of Africa relative to the South Pole did not significantly alter. Africa gives us no evidence of having drifted from a situation far to the south until comparatively late in its geological history.

The Search for a Mechanism

It has been shown that in looking for a possible means of "engineering" continental drift we must confine ourselves to processes operating within the earth. To be appropriate, the process must be capable (*a*) of disrupting the ancestral Gondwanaland into gigantic fragments, and of carrying the latter radially outwards as indicated in Fig. 210: Africa and India towards the Tethys; Australasia, Antarctica, and South America out into the Pacific; (*b*) of disrupting Laurasia, though much less drastically, and again with radially outward movements towards the Tethys and the Pacific, as indicated in Fig. 209. We have already seen that the peripheral orogenic belts probably mark the regions where opposing systems of sub-crustal currents came together and turned downwards. The movements required to account for the mountain structures are in the same directions as those required for continental drift, and it thus appears that the sub-crustal convection currents discussed on pages 408 to 413 may provide the sort of mechanism for which we are looking (Fig. 262).

To explain the peripheral orogenic belts three systems of convection currents are called for (or three co-ordinated groups of systems), with their ascending centres situated beneath Gondwanaland, Laurasia, and the Pacific respectively. Incidentally, it should be noticed that the coalescence of the usual chaotic or small convective systems into three gigantic ones involves a coincidence that can rarely have happened in the earth's history, and one that is just as likely to have come about during the Mesozoic era as at any other time. The often-asked question: How is it that Pangæa did not begin to break up and unfold until Mesozoic time? thus ceases to have any significance. If continental drift could have been caused by the gravitational forces invoked by Wegener, then it should have occurred once and for all very early in the earth's history, since those forces have always been in operation. If convection currents are necessary, continental drift may have accompanied all the greater paroxysms of mountain building in former ages but, if so, it would usually have been on no more

than a limited scale. That there was a quite exceptional integration of effort in Mesozoic and Tertiary times is forcibly suggested by eruptions of plateau basalts and building of mountains on a scale for which it would be hard to find a parallel in any earlier age.

There are, therefore, good reasons for supposing that at this critical period of the earth's history the convective circulations became unusually powerful and well organised. Currents
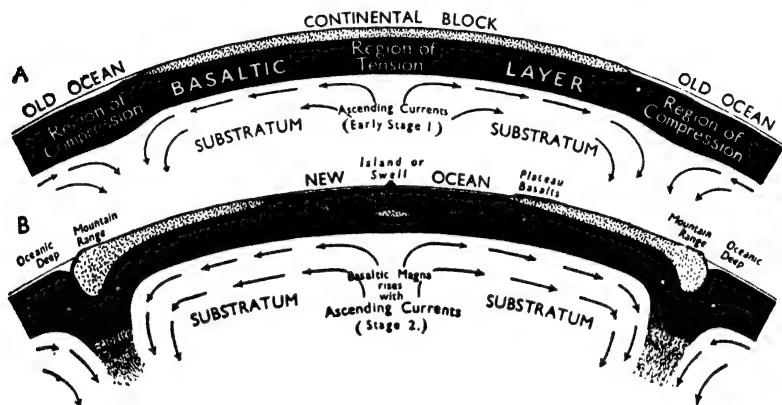
FIG. 262

Diagrams to illustrate a purely hypothetical mechanism for "engineering" continental drift. In A sub-crustal currents are in the early part of the convection cycle (Stage 1 of Fig. 215). In B the currents have become sufficiently vigorous (Stage 2 of Fig. 215) to drag the two halves of the original continent apart, with consequent mountain building in front where the currents are descending, and ocean floor development on the site of the gap, where the currents are ascending

flowing horizontally beneath the crust would inevitably carry the continents along with them, provided that the enormous frontal resistance could be overcome. The obstruction that stands in the way of continental advance is the basaltic layer, and obviously for advance to be possible the basaltic rocks must be continuously moved out of the way. In other words, they must founder into the depths, since there can be nowhere else for them to go (Fig. 262).

Now this is precisely what would be most likely to happen when two opposing currents come together and turn down-

wards beneath a cover of basaltic composition. The latter then suffers intense compression, and like the sial in similar circumstances it is eventually drawn in to form roots (*cf.* Figs. 215 and 216). On the ocean floor the expression of such a down-turning of the basaltic layer would be an oceanic deep. The great deeps bordering the island festoons of Asia and the Australasian arc (Tonga and Kermadec) probably represent the case where the sialic edge of a continent has turned down to form the inner flanks of a root, while the oceanic floor contributes the outer flanks.

It is not difficult to see that a purely basaltic root must have a very different history from one composed of sial. The density of sial is not significantly increased by compression. Consequently, when a sialic root is no longer being forcibly held down, it begins to rise in response to isostasy, heaving up a mountain range as it does so. But when rocks like basalt or gabbro (density 2·9 or 3·0) are subjected to intense dynamic metamorphism they are transformed into schists and granulites and finally into a highly compressed type of rock called *eclogite*, the density of which is about 3·4. Since this change is known to have happened to certain masses of basaltic rocks that have been involved in the stresses of mountain building, it may safely be inferred that basaltic roots would undergo a similar metamorphism into eclogite. Such roots could not, of course, exert any buoyancy, and for this reason it is impossible that tectonic mountains could ever arise from the ocean floor. On the contrary, a heavy root formed of eclogite would continue to develop downwards until it merged into and became part of the descending current, so gradually sinking out of the way, and providing room for the crust on either side to be drawn inwards by the horizontal currents beneath them (Fig. 262).

The eclogite that founders into the depths will gradually be heated up as it shares in the convective circulation. By the time it reaches the bottom of the substratum it will have begun to fuse, so forming pockets of magma which, being of low density, must sooner or later rise to the top. Thus an adequate source is provided for the unprecedented flows of plateau basalt that broke through the continents during Jurassic and Tertiary

times. Most of the basaltic magma, however, would naturally rise with the ascending currents of the main convectional systems until it reached the torn and outstretched crust of the disruptive basins left behind the advancing continents or in the heart of the Pacific. There it would escape through innumerable fissures, spreading out as sheet-like intrusions within the crust, and as submarine lava flows over its surface. Thus, in a general way, it is possible to understand how the gaps rent in the crust come to be healed again ; and healed, moreover, with exactly the right sort of material to restore the basaltic layer. To sum up : during large-scale convective circulation the basaltic layer becomes a kind of endless travelling belt on the top of which a continent can be carried along, until it comes to rest (relative to the belt) when its advancing front reaches the place where the belt turns downwards and disappears into the earth.

To go beyond the above indication that a mechanism for continental drift is by no means inconceivable would at present be unwise. Many serious difficulties still remain unsolved. In particular, it must not be overlooked that a successful process must also provide for a general drift of the crust over the interior : a drift with a northerly component on the African side sufficient to carry Africa over the Equator, and Britain from the late Carboniferous tropics to its present position. The northward push of Africa and India, of which the Alpine system and the high plateau of Tibet are spectacular witnesses, could not have been sufficient by itself to shove Europe and Asia so far to the north. To achieve this the aid of exceptionally powerful sub-Laurasian currents directed towards the Pacific is required. The total northward components might then overbalance the southward components, and a general drift of the crust would be superimposed on the normal radial directions of drift.

It must be clearly realised, however, that purely speculative ideas of this kind, specially invented to match the requirements, can have no scientific value until they acquire support from independent evidence. The detailed complexity of convection systems, and the endless variety of their interactions and

kaleidoscopic transformations, are so incalculable that many generations of work, geological, experimental, and mathematical, may well be necessary before the hypothesis can be adequately tested. Meanwhile it would be futile to indulge in the early expectation of an all-embracing theory which would satisfactorily correlate all the varied phenomena for which the earth's internal behaviour is responsible. The words of John Woodward, written in 1695 about ore deposits, are equally applicable to-day in relation to continental drift and convection currents : " Here," he declared, " is such a vast variety of phenomena and these many of them so delusive, that 'tis very hard to escape imposition and mistake."

SUGGESTIONS FOR FURTHER READING

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